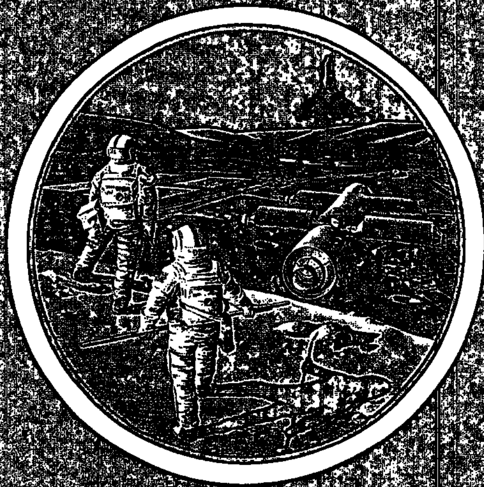
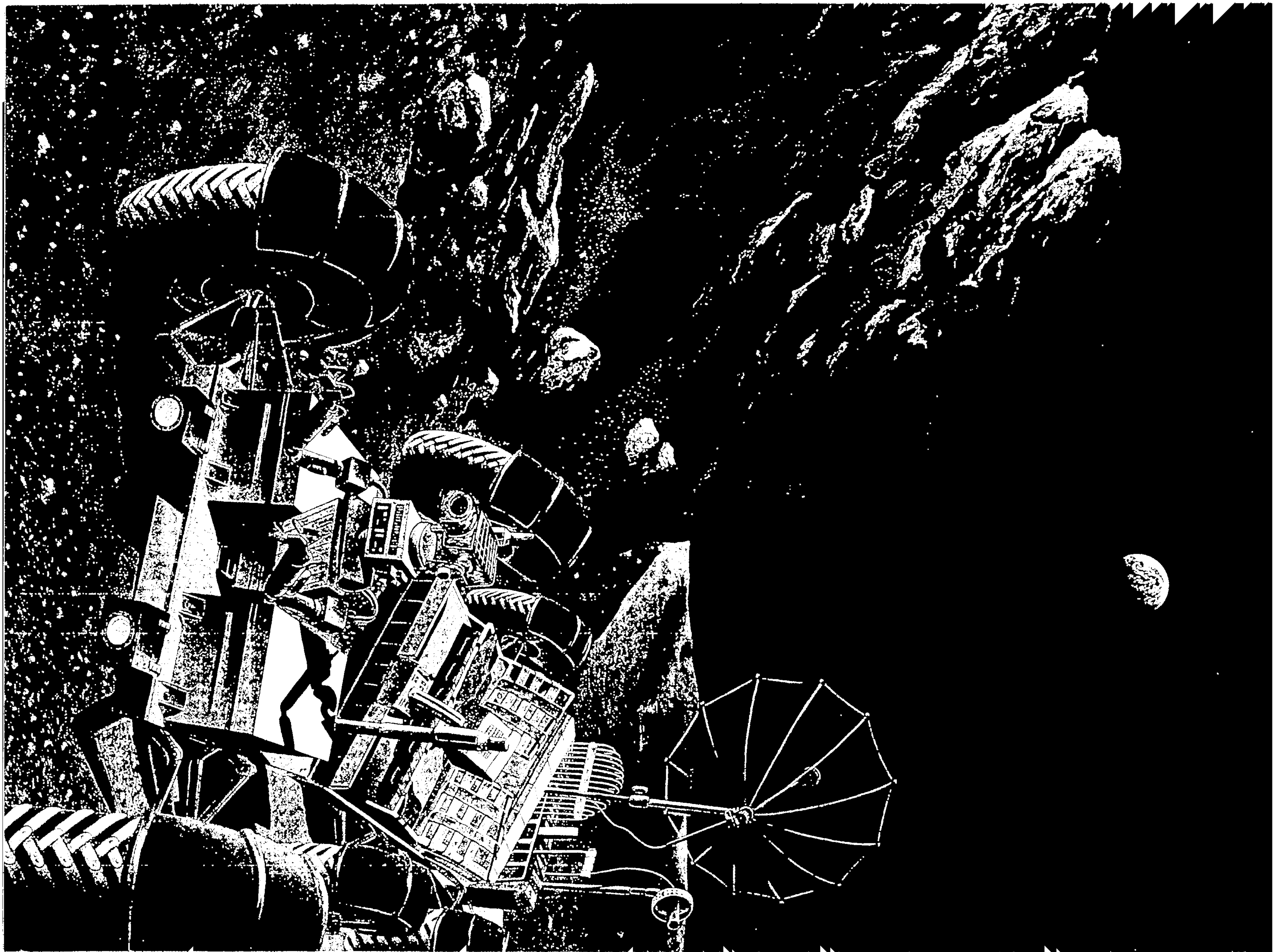
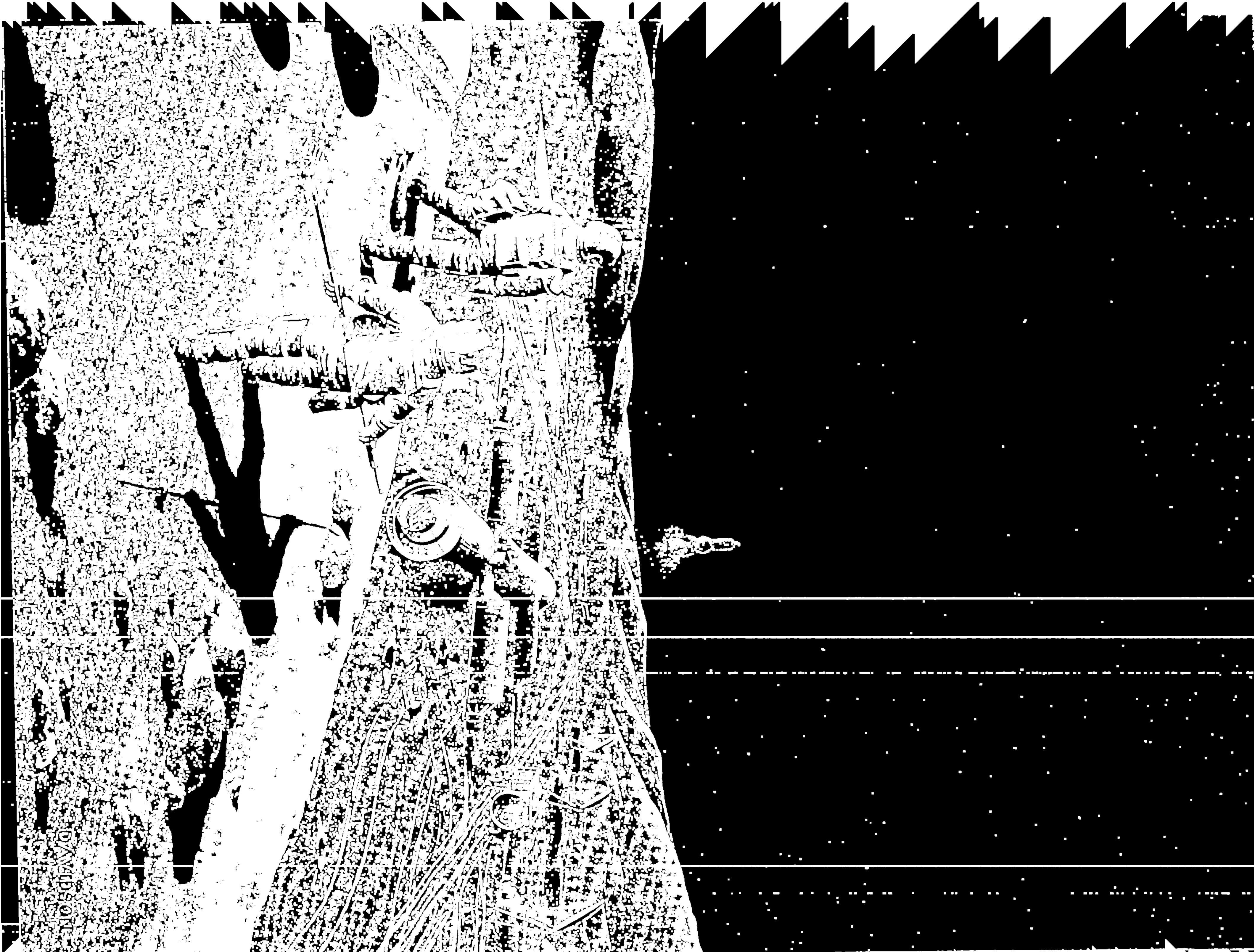
NASA SP-509

SPACE RESOURCES



Overview





Frontispiece

Advanced Lunar Base

In this panorama of an advanced lunar base, the main habitation modules in the background to the right are shown being covered by lunar soil for radiation protection. The modules on the far right are reactors in which lunar soil is being processed to provide oxygen. Each reactor is heated by a solar mirror. The vehicle near them is collecting liquid oxygen from the reactor complex and will transport it to the launch pad in the background, where a tanker is just lifting off. The mining pits are shown just behind the foreground figure on the left. The geologists in the foreground are looking for richer ores to mine.

Artist: Dennis Davidson

Space Resources

Overview

Editors

Mary Fae McKay, David S. McKay, and Michael B. Duke

**Lyndon B. Johnson Space Center
Houston, Texas**

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Preface

Space resources must be used to support life on the Moon and exploration of Mars. Just as the pioneers applied the tools they brought with them to resources they found along the way rather than trying to haul all their needs over a long supply line, so too must space travelers apply their high technology tools to local resources.

The pioneers refilled their water barrels at each river they forded; moonbase inhabitants may use chemical reactors to combine hydrogen brought from Earth with oxygen found in lunar soil to make their water. The pioneers sought temporary shelter under trees or in the lee of a cliff and built sod houses as their first homes on the new land; settlers of the Moon may seek out lava tubes for their shelter or cover space station modules with lunar regolith for radiation protection. The pioneers moved further west from their first settlements, using wagons they had built from local wood and pack animals they had raised; space explorers may use propellant made at a lunar base to take them on to Mars.

The concept for this report was developed at a NASA-sponsored summer study in 1984. The program was held on the Scripps campus of the University of California at San Diego (UCSD), under the auspices of the American Society for Engineering Education (ASEE). It was jointly managed by the California Space Institute and the Lyndon B. Johnson Space Center, under the direction of the Office of Aeronautics and Space Technology (OAST) at NASA Headquarters. The study participants (listed in the addendum) included a group of 18 university teachers and researchers (faculty fellows) who were present for the entire 10-week period and a larger group of attendees from universities, Government, and industry who came for a series of four 1-week workshops.

The organization of this report follows that of the summer study. *Space Resources* consists of a brief overview and four detailed technical volumes: (1) Scenarios; (2) Energy, Power, and Transport; (3) Materials; (4) Social Concerns. Although many of the included papers got their impetus from workshop discussions, most have been written since then, thus allowing the authors to base new applications on established information and tested technology. All these papers have been updated to include the authors' current work.

This overview, drafted by faculty fellow Jim Burke, describes the findings of the summer study, as participants explored the use of space resources in the development of future space activities and defined the necessary research and development that must precede the practical utilization of these resources. Space resources considered included lunar soil, oxygen derived from lunar soil, material retrieved from near-Earth asteroids, abundant sunlight, low gravity, and high vacuum. The study participants analyzed the direct use of these resources, the potential demand for products from them, the techniques for retrieving and processing space resources, the necessary infrastructure, and the economic tradeoffs.

This is certainly not the first report to urge the utilization of space resources in the development of space activities. In fact, *Space Resources* may be seen as the third of a trilogy of NASA Special Publications reporting such ideas arising from similar studies. It has been preceded by *Space Settlements: A Design Study* (NASA SP-413) and *Space Resources and Space Settlements* (NASA SP-428).

And other, contemporaneous reports have responded to the same themes. The National Commission on Space, led by Thomas Paine, in *Pioneering the Space Frontier*, and the NASA task force led by astronaut Sally Ride, in *Leadership and America's Future in Space*, also emphasize expansion of the space infrastructure; more detailed exploration of the Moon, Mars, and asteroids; an early start on the development of the technology necessary for using space resources; and systematic development of the skills necessary for long-term human presence in space.

Our report does not represent any Government-authorized view or official NASA policy. NASA's official response to these challenging opportunities must be found in the reports of its Office of Exploration, which was established in 1987. That office's report, released in November 1989, of a 90-day study of possible plans for human exploration of the Moon and Mars is NASA's response to the new initiative proposed by President Bush on July 20, 1989, the 20th anniversary of the Apollo 11 landing on the Moon: "First, for the coming decade, for the 1990s, Space Station *Freedom*, our critical next step in all our space endeavors. And next, for the new century, back to the Moon, back to the future, and this time, back to stay. And then a journey into tomorrow, a journey to another planet, a manned mission to Mars." This report, *Space Resources*, offers substantiation for NASA's bid to carry out that new initiative.

Introduction

Future space activities may benefit from the use of natural resources found in space: energy from the Sun, certain properties of space environments and orbits, and materials of the Moon and near-Earth asteroids. To assess this prospect and to define preparations that could lead to realizing it, a study group convened for 10 weeks in the summer of 1984 at the California Space Institute at the University of California at San Diego. Papers written by this study group were edited and then recycled through most of the contributors for revision and updating to reflect current thinking and new data on these topics. This is a summary report of the group's findings.

The sponsors of the study—NASA and the California Space Institute—charged the study group with the task of defining possible space program objectives and scenarios up to the year 2010 and describing needed technologies and other precursor actions that could lead to the large-scale use of nonterrestrial resources. We examined program goals and options to see where, how, and when space resources could be of most use. We did not evaluate the long-range program options and do not recommend any of them in preference to others. Rather, we concentrated on those near-term actions that would enable intelligent choices among realistic program options in the future. Our central conclusion is that near-Earth resources can indeed foster the growth of human activities in space. Most uses of the resources are within the space program, the net product being capabilities and information useful to our nation both on and off the Earth.

The idea of using the energy, environments, and materials of space to support complex activities in space has been implicit in many proposals and actions both before and during the age of space flight. As illustrated in figure 1, the deep gravity well of the Earth makes it difficult and expensive to haul all material supplies, fuel, and energy sources into space from the surface of the Earth; it is clearly more efficient to make maximum use of space resources. Up to now, however, our ability to employ these resources has been limited by both technology and policy. Studies and laboratory work have failed to bring the subject much beyond the stage of speculations and proposals, primarily because until now there has been no serious intent to establish human communities in space.

With progress in the Soviet program of long-duration manned operations in Earth orbit and with the coming of an American space station initiative, the picture appears to be changing. The present study is one step in a process laying groundwork for the time when living off Earth, making large-scale use of nonterrestrial resources, will be both technologically feasible and socially supported.

Findings of the Summer Study

The 18 faculty fellows who participated in the summer study organized themselves into four groups. The focus of each group corresponded with that of a 1-week workshop held in conjunction with the summer study and attended by 10 to 20 experts in the target field. The first working group generated the three scenarios that formed the basis of the subsequent discussions. The other three groups focused on these areas of inquiry:

- Working group 2–Energy, power, and transport
- Working group 3–Materials and processing
- Working group 4–Human and social concerns

In what follows, our findings are presented in the order of these topics, but they are offered as findings of the summer study as a whole. Integrated in these findings are the views of the faculty fellows and the workshop attendees.

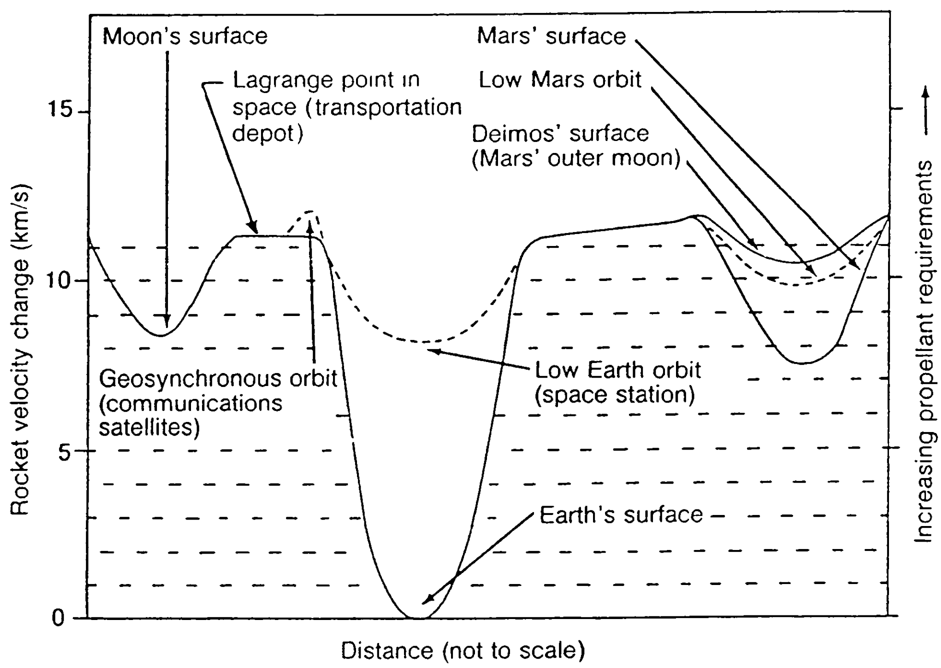


Figure 1

The Gravity Well of the Earth

The Earth sits in a deep gravity well and considerable rocket energy is necessary to lift material from that well and put it into space. The rocket velocity change (ΔV) shown here is an indication of the minimum fuel needed to travel to low Earth orbit and to other places, including the lunar surface and Deimos. Not shown on the diagram but also important is the fact that it takes less ΔV to reach some Earth-crossing asteroids than it does to reach the lunar surface, about 10 percent less for asteroid 1982 DB, for example. This diagram is not a potential energy diagram, as the ΔV depends on the path taken as well as the potential energy difference. However, it is a good indication of the relative fuel requirements of transportation from one place to another. The diagram also does not take into account travel times corresponding to minimum ΔV trajectories. One-way travel times range from less than an hour to low Earth orbit to 3 days for lunar orbit to months to a year or more for Mars and Earth-crossing asteroids.

Future Space Activities

Before we could evaluate the benefits and opportunities associated with the use of space resources, we had to consider what might be going on in space in the future. The target date defined for this study, 2010, is beyond the projection of present American space initiatives but not too far in the future for reasonable technological forecasting. The U.S. space program is now set on a course that can carry it to the end of this century, with increasing capabilities in low Earth orbit (LEO) and geosynchronous Earth orbit (GEO) and modest extensions into deeper space. At the present rate of progress, there would not be much new opportunity to exploit nonterrestrial resources before the year 2000.

A typical plan for space activities is illustrated in figure 2, which shows a sequence of milestones leading to human enterprises in LEO, in GEO, and on the Moon, plus automated probing of some near-Earth asteroids and of Mars. In this plan, most of the space activity before 2010 is concentrated in low Earth orbit, where the basic space station is expanded into a

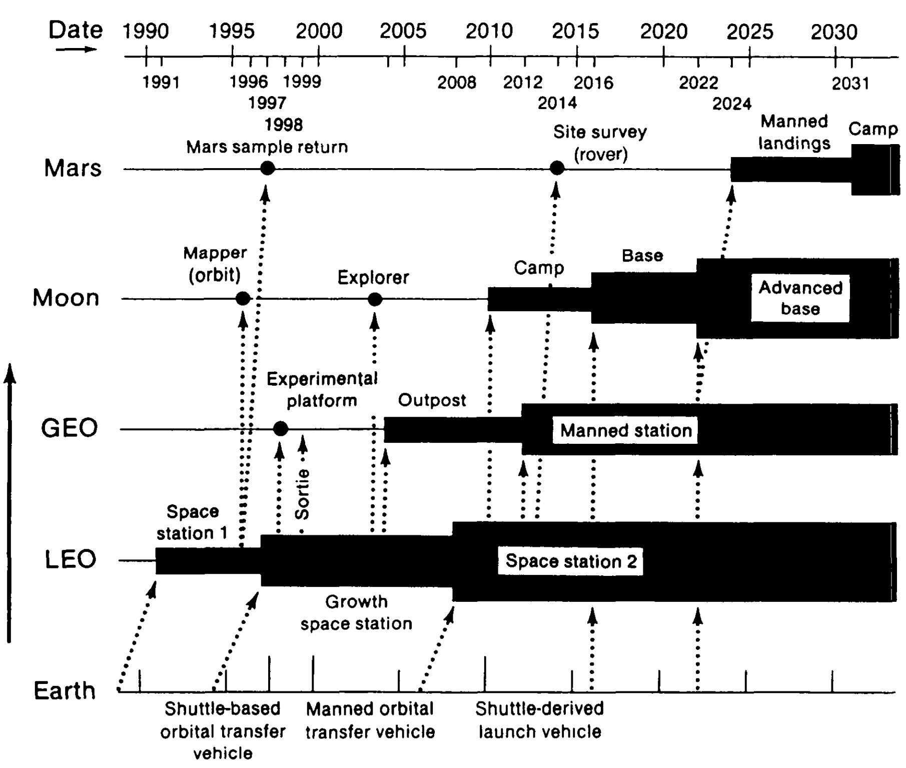


Figure 2

Baseline Scenario

If NASA continues its business as usual without a major increase in its budget and without using nonterrestrial resources as it expands into space, this is the development that might be expected in the next 25 to 50 years. The plan shows an orderly progression in manned missions from the initial space station in low Earth orbit (LEO) expected in the 1990s, through an outpost and an eventual space station in geosynchronous Earth orbit (GEO) (from 2004 to 2012), to a small lunar base in 2016, and eventually to a Mars landing in 2024. Unmanned precursor missions would include an experiment platform in GEO, lunar mapping and exploration by robot, a Mars sample return, and an automated site survey on Mars. This plan can be used as a baseline scenario against which other, more ambitious plans can be compared.

Figure 3

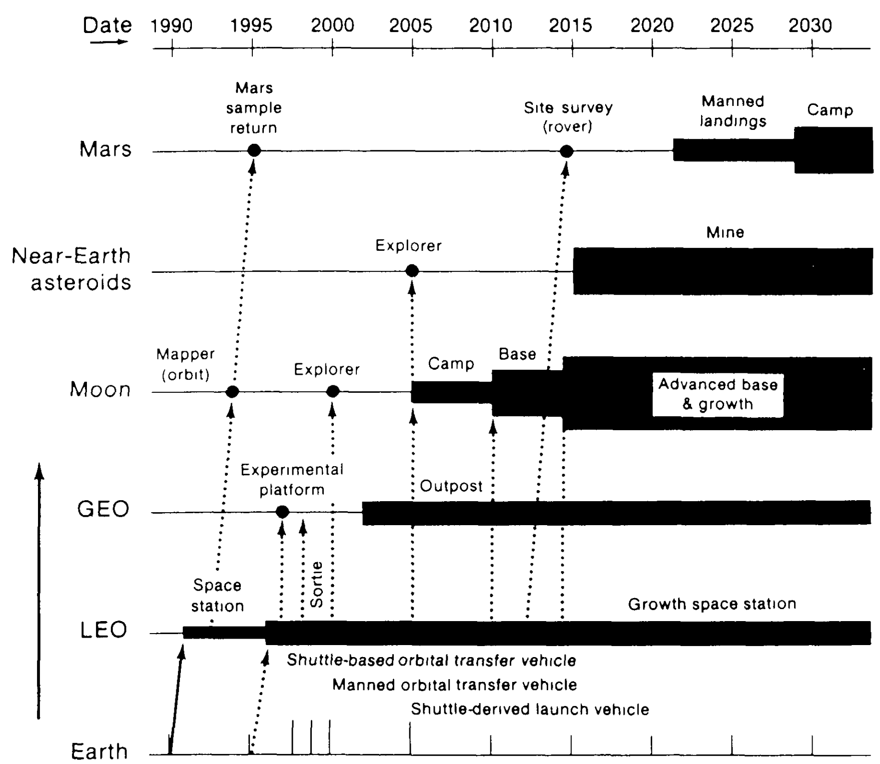
Scenario for Space Resource Utilization

Space resource utilization, a feature lacking in the baseline plan, is emphasized in this plan for space activities in the same 1990-2035 timeframe. As in the baseline scenario, a space station in low Earth orbit (LEO) is established in the early 1990s. This space station plays a major role in staging advanced missions to the Moon, beginning about 2005, and in exploring near-Earth asteroids, beginning about the same time These exploration activities lead to the establishment of a lunar camp and base which produce oxygen and possibly hydrogen for rocket propellant. Automated missions to near-Earth asteroids begin mining these bodies by about 2015, producing water and metals which are returned to geosynchronous Earth orbit (GEO), LEO, lunar orbit, and the lunar surface. Oxygen, hydrogen, and metals derived from the Moon and the near-Earth asteroids are then used to fuel space operations in Earth-Moon space and to build additional space platforms and stations and lunar base facilities These space resources are also used as fuel and materials for manned Mars missions beginning in 2021. This scenario might initially cost more than the baseline scenario because it takes large investments to put together the facilities necessary to extract and refine space resources. However, this plan has the potential to significantly lower the cost of space operations in the long run by providing from space much of the mass needed for space operations.

larger complex over a period of 20 years. In geosynchronous Earth orbit, an experimental platform is replaced in 2004 by an outpost to support manned visits leading to a permanently manned station by 2012. Until the year 2010 only unmanned missions are sent to the Moon. In that year, nearly 20 years after the establishment of the space station, a small lunar camp is established to support short visits by people. In this plan, the only American missions to Mars in the next 40 years are two unmanned visits: a sample return mission and a roving surveyor.

It is clear that, if the plan in figure 2 is followed, natural resources from the Moon, Mars, or other planetary bodies will not be used until at least 2016.

If we consider the plan in figure 2 to be our baseline, then figure 3 illustrates an alternative departing from that baseline in the direction of more and earlier use of nonterrestrial resources. In this plan, a growing lunar base has become a major goal after the space station. Lunar and asteroidal resources would be sought and exploited in



support of this goal rather than for any external purpose. The establishment of a lunar camp is moved up 5 years to 2005 and an advanced lunar base is in place by 2015. In this plan, lunar resources are used to support the construction and operation of this base and lunar-derived oxygen is used to support transportation to and from the base. Asteroidal material from automated mining missions would also contribute to supporting these space operations after 2015.

Figure 4 shows a different departure from the baseline. Here, the objectives are balanced among living off Earth, developing near-Earth resources for a variety of purposes, and further exploring the solar system with an eventual human landing on Mars. In this alternative scenario, a LEO space station, a small manned GEO outpost, and a small manned lunar station are all in operation by 2005, with a manned Mars visit and establishment of a camp by 2010, some 12 to 14 years earlier than in

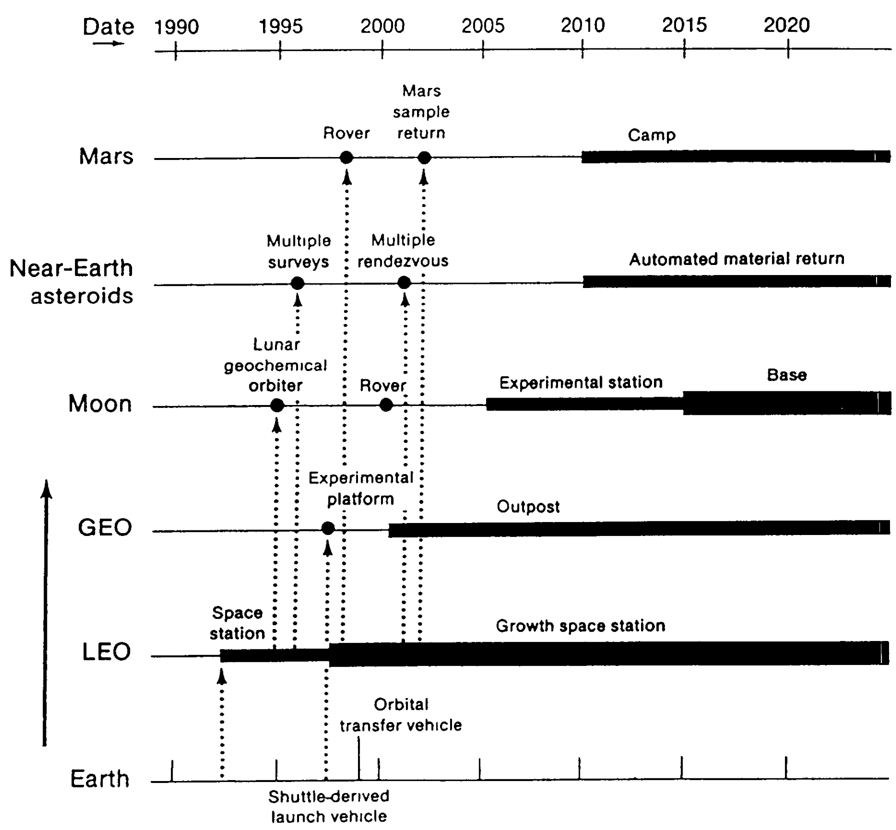


Figure 4

Scenario for Balanced Infrastructure Buildup

In this scenario, each location in space receives attention in a balanced approach and none is emphasized to the exclusion of others. The scenario begins with the establishment of the initial space station about 1992. This is followed by the establishment of a manned outpost in geosynchronous Earth orbit (GEO) in 2001, an experimental station on the Moon in 2006, and a manned Mars camp in 2010. In parallel with these manned activities, many automated missions are flown, including a lunar geochemical orbiter and a lunar rover, multiple surveys of near-Earth asteroids and rendezvous with them, and a martian rover and a Mars sample return. Automated mining of near-Earth asteroids beginning in 2010 is also part of this scenario.

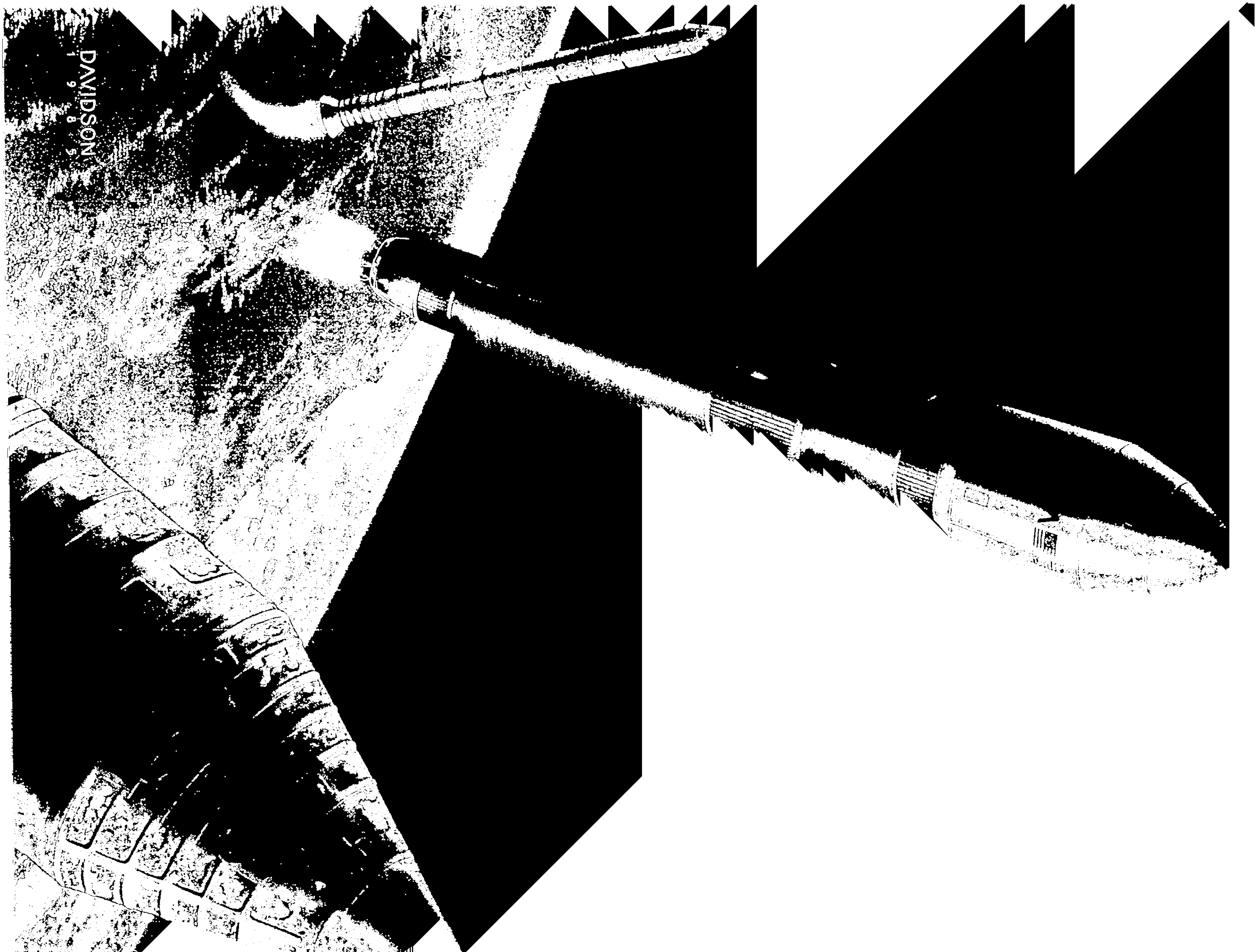
the previous plans. Automated asteroid mining and return starts by 2010. The focus of this program is longer term than that of the program diagramed in figure 3. By building up a balanced infrastructure at various locations, it invests more effort in activities whose benefits occur late in the next century and less in shorter range goals such as maximizing human presence on the Moon.

These three scenarios, the baseline and two alternates, have served as a basis for our discussion of the uses of nonterrestrial resources. None is a program recommended by the study group, since that was not our charter. They are merely illustrative examples of programs that, we believe, might materialize over the next two decades as a result of national or international trends in space. The two alternate scenarios assume some acceleration and focusing of American efforts in space, as happened during the Apollo era, while the baseline scenario assumes a straightforward extrapolation of our present program, with only modest budget growth and no particular concentration on the use of nonterrestrial resources.

Heavy Lift Launch Vehicle

An unmanned heavy lift launch vehicle derived from the Space Shuttle to lower the cost of transporting material to Earth orbit would make it feasible to transport to orbit elements of a lunar base or a manned spacecraft destined for Mars. Its first stage would be powered by two solid rocket boosters, shown here after separation. Its second stage would be powered by an engine cluster at the aft end of the fuel tank that forms the central portion of the vehicle. All this pushes the payload module located at the forward end. This payload module can carry payloads up to 30 feet (9.1 meters) in diameter and 60 feet (18.3 meters) in length and up to 5 times as heavy as those carried by the Shuttle orbiter.

Artist: Dennis Davidson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Energy, Power, and Transport

We became convinced that a space program large enough to need, and to benefit significantly from, nonterrestrial resources would require a great expansion of energy, power, and transport beyond the capabilities of today. Sunlight is already in use as a primary energy source in space, and nuclear energy has been used on a small scale. Photovoltaic panels, together with chemical or nuclear energy sources brought from Earth, have been sufficient up to now. In the future, more advanced and much larger solar and nuclear energy systems may be built; but, even then, energy supply may limit our rate of progress. For example, a program is under way to develop the SP-100, a space nuclear power plant intended to produce 100 kilowatts of electricity with possible extension to a megawatt. But even a small lunar base would consume several megawatts.

Harnessing sunlight on a large scale and at low cost thus remains a priority research and development goal, as does the creation of high-capacity systems for converting and storing solar and nuclear energy in space. Many studies have described the candidate techniques, including solar furnaces, solar-powered steam engines, solar-pumped lasers, and nuclear thermal power plants.

Although solar energy is ubiquitous and abundant, and compact nuclear energy sources can be brought up from Earth, it is still necessary to have machinery in space for capturing, storing, converting, and using the energy. Perhaps nonterrestrial resources can be used in the creation of some of this machinery. For example, as has often been proposed, lunar silicon could be used for photovoltaics; lunar glass, for mirrors.

A more important energy initiative might be the development of new storage and management concepts, such as the establishment of water, oxygen, and hydrogen caches cryogenically stored in the lunar polar cold traps. Fluidized-bed heat storage, molten metal cooling fountains, and storage by hoisting weights are other examples of energy storage and management benefiting from attributes of the lunar environment; namely, a large supply of raw materials, vacuum, and gravity. Consideration should also be given to the siting of solar and nuclear power plants on the Moon. For example, a solar plant located at one of the lunar poles would be capable of nearly continuous operation, in contrast to a plant at an equatorial location which would be in darkness 14 days out of 28 (figs. 5 and 6).

We found that transport costs would be dominant in any program

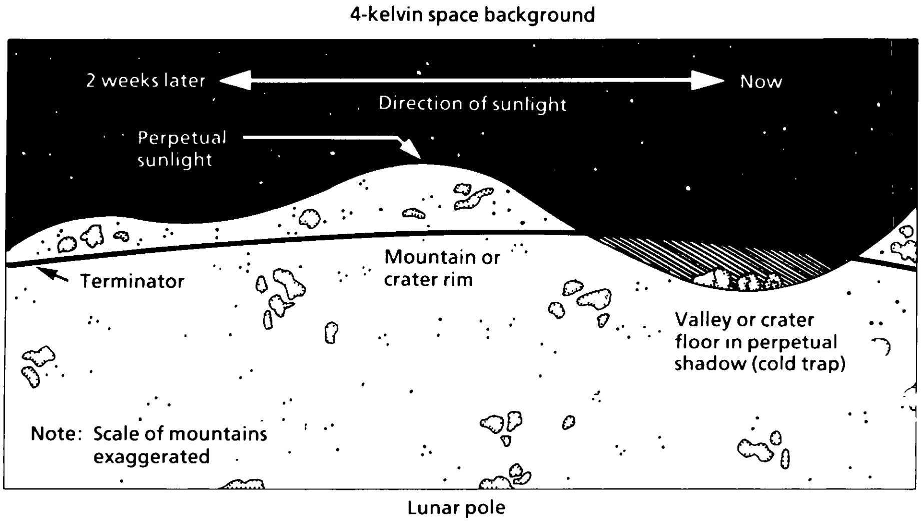


Figure 5

Lunar Polar Illumination

The Moon's diurnal cycle of 14 Earth days of sunlight followed by 14 Earth days of darkness could be a problem for siting a lunar base dependent on solar energy or cryogenic storage. A site that might obviate this problem would be at one of the lunar poles. At a pole, high points, such as mountain tops or crater rims, are almost always in the sunlight and low areas, such as valleys or crater floors, are almost always in the shade. The Sun as seen by an observer at the pole would not set but simply move slowly around the horizon. Thus, a lunar base at a polar location could obtain solar energy continuously by using mirrors or collectors that slowly rotated to follow the Sun And cryogens, such as liquid oxygen, could be stored in shaded areas with their constant cold temperatures

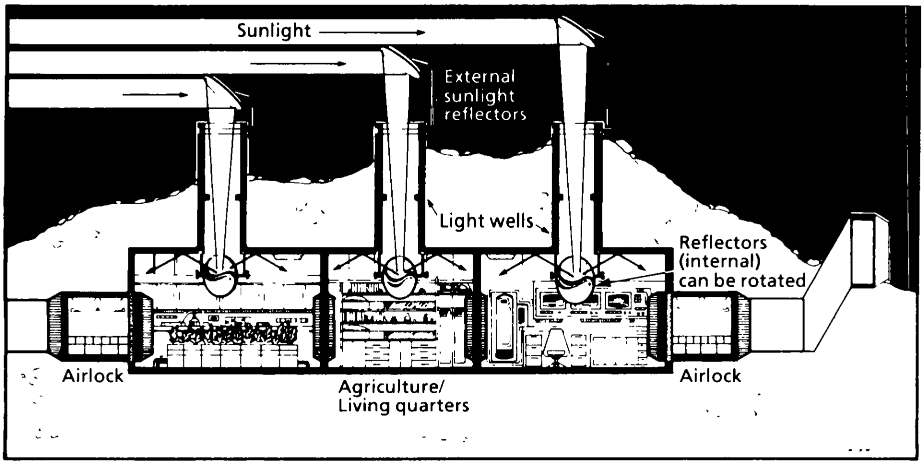


Figure 6

Polar Lunar Base Module

Light could be provided to a lunar base module located at the north (or south) pole by means of rotating mirrors mounted on top of light wells. As the mirrors tracked the Sun, they would reflect sunlight down the light wells into the living quarters, workshops, and agricultural areas. Mirrors at the bottom of the light wells could be used to redirect the sunlight or turn it off.

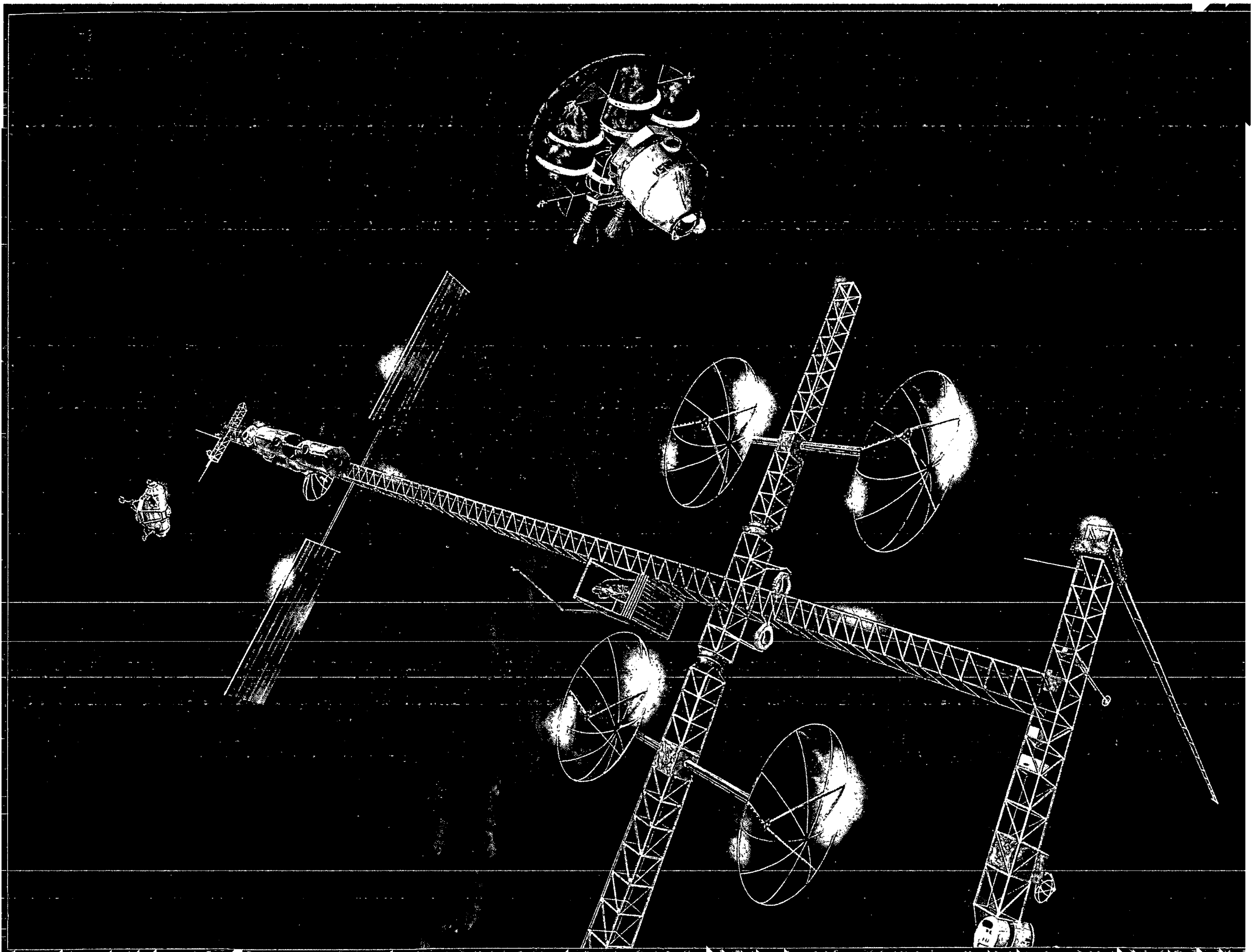
large enough to make significant use of nonterrestrial resources. We recommend continued pursuit of technologies offering the prospect of large reductions in Earth-to-LEO transport cost. A preliminary economic model of the effect of lunar resource utilization on the cost of transportation in space was developed by the study. This model, developed in more detail, shows that delivery of lunar-derived oxygen to LEO for use as propellant in space operations would be significantly cheaper than delivery of the same payload by the Space Shuttle, assuming a demand for about 300 metric tons of oxygen delivered to LEO. If Earth-to-LEO costs could be reduced using unmanned cargo rockets—Shuttle-derived launch vehicles or heavy lift launch vehicles, the cost of lunar-derived oxygen would also be reduced. At this demand level, if Earth-to-LEO costs were lowered to about 2/3 their present value, it would be cheaper to bring all oxygen up from Earth. But, if demand for liquid oxygen as propellant in LEO were to grow by a factor of 2 or more, then lunar-derived oxygen would be competitive with Earth-derived oxygen using any currently contemplated launch vehicle. This model points out that considerable reduction in unit cost for lunar-derived oxygen delivered to LEO can be achieved as the volume and scale of operations increase. The model assumes that all hydrogen is transported from Earth. If lunar-derived hydrogen were available, the cost of providing lunar-derived oxygen would be considerably reduced at all production rates.

While enhancing Earth-to-orbit capacity, we should be preparing to expand our range. For example, an orbital transfer vehicle (OTV) is needed for traffic to and from GEO. Extending the space-based OTV concept to meet the needs of a lunar base transport system should be considered from the outset of OTV development. The development of an efficient OTV capable of LEO-to-Moon transportation was identified by the economic model just summarized as the single most important factor in the cost of supplying lunar-derived oxygen to space operations.

Also, we support the findings of other studies, such as NASA's 1979 report *Space Resources and Space Settlements*, to the effect that it may be practical and desirable to transport lunar material using means other than the OTV-derived vehicles that will be carrying humans to and from the Moon. The lunar environment encourages consideration and development of electromagnetic launchers and other unconventional transport devices.

We recognize a need for transport of both equipment and personnel from place to place on the lunar surface and probably also a need for at least short-range transport of raw and processed lunar materials. Much of this transport would logically be provided by teleoperated vehicles. Teleoperated systems, robotics, and automation developed for the space station may have direct application in lunar operations. Such systems would be absolutely required by any program to mine and utilize material from near-Earth asteroids.

Finally, we recommend that alternative advanced propulsion technologies be developed to permit comparison and selection of systems for transport beyond Earth orbit. Examples include solar thermal propulsion, solar electric ion thrusters, nuclear electric propulsion, laser-powered systems, and light-pressure sailing.



Locations, Environments, and Orbits

Another natural resource is afforded by orbits and places in the solar system. The geosynchronous orbit, used for communications and observation, is a resource that has led to the largest commercial development in space and offers an even greater payoff in the future. The combined gravity fields of the Sun and planets offer a resource that has already been used for modifying and controlling spacecraft trajectories through swingby maneuvers. Aeromaneuvering in planetary atmospheres and momentum exchanges using tethers offer additional means of trajectory control.

In future space activities, unique space environments may become important resources. Examples include the Moon's far side, which is shielded from the radio noise of Earth and would thus be an excellent location for a deep-space radio telescope. Lunar orbit or the gravitationally stable Lagrangian points in the Earth-Moon-Sun system may be good locations for space platforms. As has already been pointed out, the lunar poles have the potential of providing constant sunlight to power a lunar base. And aerobraking in the Earth's upper atmosphere may make it possible to bring both lunar and asteroidal material into low Earth orbit for use in space activities.

We found that any future program intending to make major use of nonterrestrial resources, especially the materials of the Moon, must include a substantial human presence beyond Earth orbit. This finding leads to the conclusion that some form of extended human living in deep space, such as a lunar base, is a necessity (fig. 7).

The space station is the obvious place to conduct the proving experiments that will enable confident progress toward productive lunar living, including use of local resources. While this summer study group did not attempt to lay out an entire plan of events leading up to establishment of a lunar base, we recognized some of the steps that are logical and likely to be considered essential. One of these is a suite of experiments, in the space station, demonstrating the soundness of methods and processes to be used at the lunar base.

Since a number of these methods and processes are gravity-dependent, it is necessary to demonstrate them at simulated lunar gravity, 1/6 *g*, and this cannot be done on Earth. We therefore recommend that space station facilities include a 1/6 *g* centrifuge in which lunar base experiments and confirmation tests can be carried out.

Lunar Orbit Space Station

Proximity to lunar-derived propellant and materials would make a space station in orbit around the Moon an important transportation node. It could serve as a turnaround station for lunar landing vehicles which could ferry up liquid oxygen and other materials from the lunar surface. An orbital transfer vehicle could then take the containers of liquid oxygen (and possibly lunar hydrogen) to geosynchronous or low Earth orbit for use in many kinds of space activities. A lunar orbit space station might also serve as a staging point for major expeditions to other parts of the solar system, including Mars.

Artist: Michael Carroll

Figure 7

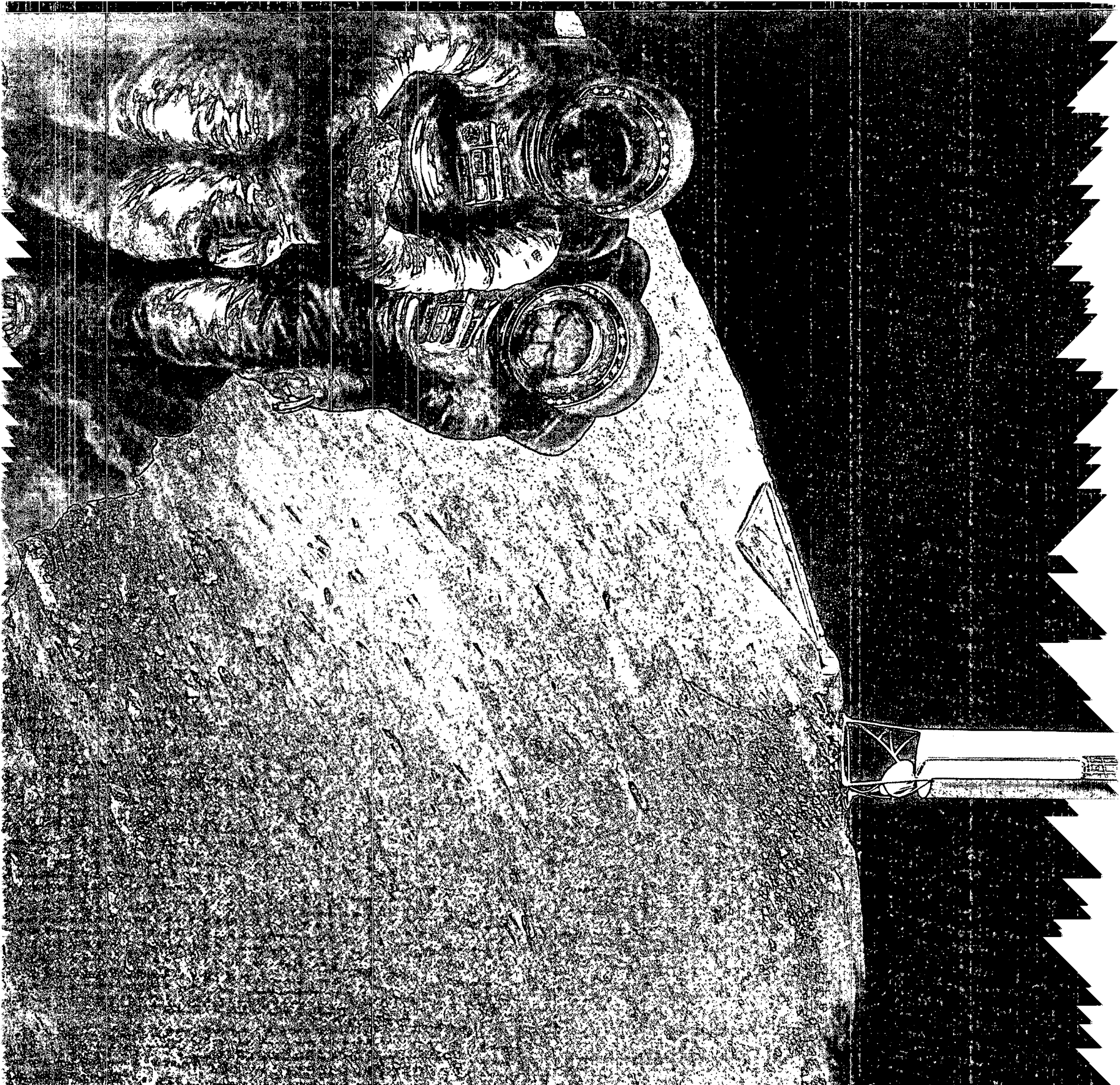
Advanced Lunar Base

In this artist's conception of a lunar base, a processing plant in the foreground is producing oxygen and fused glass bricks from lunar rocks and soil. The rocks and soil are fed into the system on the left side from a robot-controlled cart. Solar energy concentrated by the mirror system is used to heat, fuse, and partially vaporize the lunar material. The oxygen-depleted fused soil is cast into bricks, which are used as building blocks, paving stones, and radiation shielding. Oxygen extracted from the vapor is piped to an underground cryogenic plant, where it is liquefied and put into the round containers shown under the shed. The rocket in the background will carry these containers into space, where the oxygen will be used as rocket propellant. The lunar base living quarters are underground in the area on the left. The solar lighting system and the airlock entry are visible. As this lunar base expands, additional useful products such as iron, aluminum, and silicon could be extracted from the lunar rocks and soil.

Polar Solar Power System

At a base near a lunar pole, a solar reflector (the large tower in the background) directs sunlight to a heat collector, where it heats a working fluid which is used to run a turbine generator buried beneath the surface. At such a location the solar power tower can track the Sun simply by rotating around its vertical axis. Power is thus provided continuously without the 2-week nighttime period which is characteristic of nonpolar locations. The triangle in the background is the mining pit. In the foreground, two scientists collect rock samples for analysis at the base.

Artist: Maralyn Vicary



Materials and Processing

Any material that is already in space has enormous potential value relative to the same material that needs to be brought up from Earth, simply because of the high cost of lifting anything out of the Earth's deep gravity well. On an energy basis, it is more than 10 times as easy to bring an object into low Earth orbit from the surface of the Moon as from the surface of the Earth (see figure 1). Residual propellants and tanks or other hardware left in orbit can constitute a resource simply because of the energy previously invested in them.

These facts of nature underlie many proposals for the use of nonterrestrial materials. For example, as discussed in the transportation section, there could be a payoff if lunar oxygen, abundant in the silicates and oxides of the Moon and extractable by processes conceptually known, were to be used in large quantities for propulsion and life support in space operations. A sketch of a concept for extracting oxygen from lunar materials is shown in figure 8. Byproducts of this process might include useful metals.

The materials of near-Earth asteroids may complement the materials of the Moon. On the basis of evidence gained to date, the Moon is lacking in water and carbon compounds—important substances that are abundant in certain classes of meteorites and thus may be found among the small asteroids that orbit the Sun near us. Water from asteroids could provide hydrogen for use as rocket fuel in space operations. On an energy basis, many of the near-Earth asteroids are even easier to reach than the Moon. And there are more energy advantages in a payload return from an asteroid because of their very low gravity. This same low gravity may require novel techniques for mining asteroids (figs. 9 and 10). Low-energy transit times to asteroids are relatively long (months or years, in comparison to days for the Moon), so the voyages to obtain these asteroid materials will probably be automated rather than manned.

Our first finding with regard to materials and processing is obvious but still needs to be stated explicitly because it is so important.

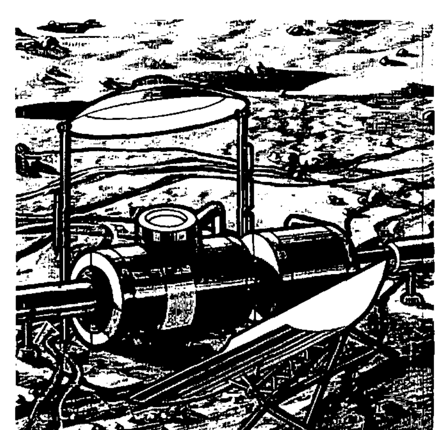


Figure 8

Solar Furnace Processing of Lunar Soil To Produce Oxygen

A device like this could utilize solar energy to extract oxygen from lunar soil. Lunar soil is fed into the reactor through the pipe on the left. Concentrated solar rays heat the soil in the furnace. Hydrogen gas piped into the device reacts with ilmenite in the soil, extracting oxygen from this mineral and forming water vapor. Ilmenite, an iron-titanium oxide, is common in lunar mare basalts. When this mineral is exposed to hydrogen at elevated temperatures (around 900°C), the following reaction takes place:

$$FeTiO_3 + H_2 \rightarrow Fe\ (metal) + TiO_2 + H_2O$$

In the device illustrated, the water vapor is removed by the unit on the right and electrolyzed to yield oxygen gas and hydrogen gas. The hydrogen gas is cycled back into the reactor. The oxygen gas is cooled and turned into liquid oxygen. Metallic iron is a useful byproduct of this reaction. The production of liquid oxygen for life support and propellant use, both on the Moon and in Earth-Moon space, is such an important economic factor that it could enable a lunar base to pay for itself.

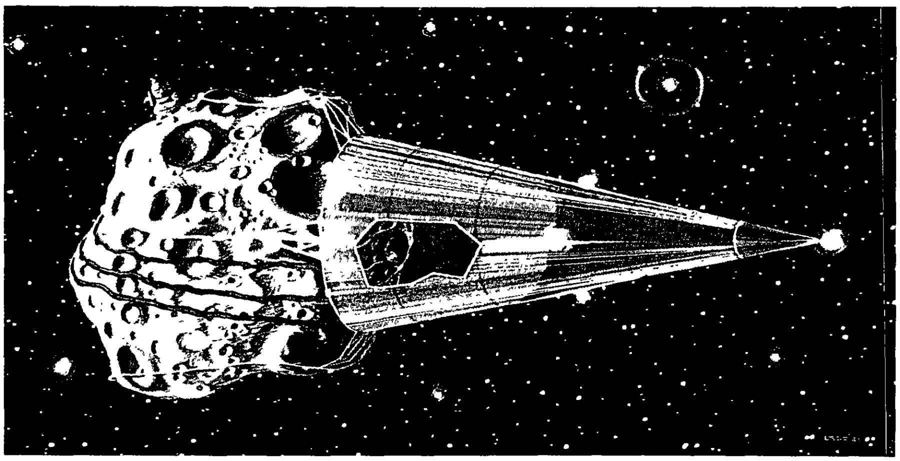


Figure 9

Tethered Asteroid

In this drawing, a small asteroid is being mined for raw materials from which water and metals can be extracted. A landing craft is shown on the surface near the top of the asteroid. Robotic devices from this craft have attached a large cone-shaped shroud with tethers which go completely around the asteroid. A small mining vehicle (see next figure), also held to the surface with tethers, uses paddle wheels to throw loose asteroid regolith up from the surface. The regolith is caught by the shroud. When full, the shroud can be propelled by attached engines or towed by another vehicle to a processing plant in Earth orbit.

The United States will have no access to nonterrestrial materials unless there is a substantial change in the national space program. Because of recent budget limits and a concentration on applications in LEO and GEO, we have no capability to send humans to the Moon. The option of an entirely automated lunar materials recovery operation, while it might be technically feasible, appears to us unlikely to gain approval. With regard to asteroidal resources, automated return to Earth orbit is mandated by trip times, but the processing would still require human supervision. These findings have two consequences: first, that the utilization of nonterrestrial materials awaits the creation of some new system for high-capacity transport beyond LEO; and, second, that large-scale utilization awaits the creation of a lunar base or an asteroid mining and recovery scenario.

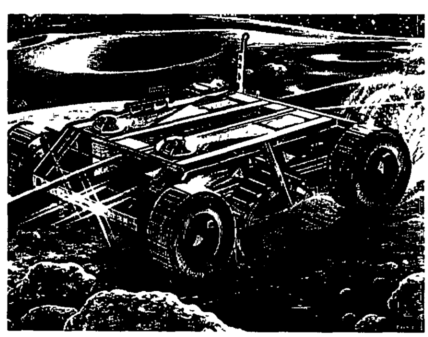


Figure 10

Asteroid Mining Vehicle

Because of asteroids' extremely low gravity, normal mining methods (scoops, etc.) may not be practical and unusual methods may be required. This innovative asteroid mining vehicle is designed to be used with the shroud shown in the previous figure. As the robotic vehicle moves across the asteroid, it is held to the surface by tethers. The vehicle has rotating paddle wheels that dig into the regolith and throw loose material out from the asteroid to be caught by the shroud. Other techniques might also be tried, such as using a tethered or anchored rig to drill or melt big holes. Tradeoff studies must be made to determine whether it is more efficient to process the raw material into useful products on or near the asteroid or to bring back only raw material to a processing plant near Earth. Because of very long transportation times (up to several years for round trips), it is probably not practical to have asteroid mining missions run by human crews. Automated, robotic, and teleoperated missions seem more practical. However, the complexity of such a mission is likely to be high.

Our other findings regarding lunar, asteroidal, and martian materials presume that the nation has found some way to get over the hurdles just described. With the required transport and habitat infrastructure in place, the question reduces to one of considering possible ways to process and use the materials.

Lunar oxygen, raw lunar soil, lunar "concretes," lunar and asteroidal metals, and asteroidal carbonaceous and volatile substances may all play a part in the space economy of the future.

Because oxygen typically constitutes more than three-quarters of the total mass launched from Earth, an economical lunar oxygen source would greatly reduce Earth-based lift demands. Since transport to LEO accounts for a major portion of the total program cost, use of nonterrestrial propellants may permit faster growth of any program at a given budget level.

Another potential use of nonterrestrial resources is in construction, ranging from the simple use of raw lunar soil as shielding to the creation of refined industrial products for building large structures in space.

At the outset, we believe that lunar material will be used rather crudely; for example, by piling it on top of habitat structures brought from Earth. Even that conceptually simple use implies a significant dirt-moving capacity on the Moon. In any event, the use of local material for radiation and thermal shielding is probably essential because of the prohibitive cost of bringing up an equivalent mass from Earth.

Going beyond just raw soil, it is reasonable to ask whether or not a structural material equivalent to concrete could be created on the Moon. Studies by experts in the cement industry suggest that lunar concrete is a possibility, especially if large amounts of energy and some water are available (figs. 11 and 12). Even without water, it may be possible to process lunar soil into forms having compressive and shear strength, hence usable

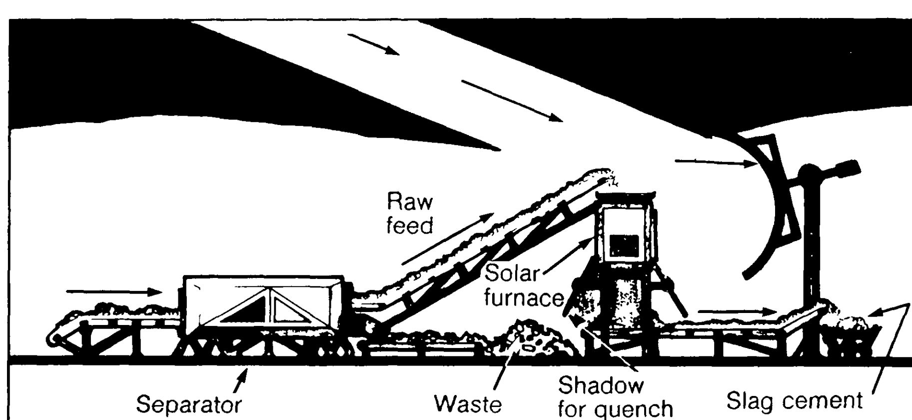


Figure 11

Slag Cement Production Facility

It seems possible to make a usable cement on the lunar surface by relatively simple means. Feedstock separated from lunar soil would be melted in a solar furnace and then quenched in shadow to form a reactive glassy product. When this product is mixed with water and aggregate and allowed to react and dry, it should make a coherent concrete suitable for many structures at a lunar base.

in structures. Examples include sintered soil bricks, cast glass products, and fiberglass.

Metals are also available on the Moon and asteroids. Metallic iron-nickel is a major component of most meteorites and probably most asteroids. Meteoritic iron, extracted magnetically from lunar soils, can be melted and used directly. Ultrapure iron, which could be produced in the Moon's vacuum and which would not rust even in the moist oxygenated air of a lunar habitat, may prove to be a valuable structural material. Other metals, including titanium and aluminum, are abundant on the Moon but are bound in oxides and silicates so that their extraction is more difficult.

In an early lunar base, the air, water, and food to support human life will have to be supplied from Earth. As experience is gained, both in a LEO space station and on the Moon, recycling will become more practical, allowing partial closure of the life support system and greatly reducing

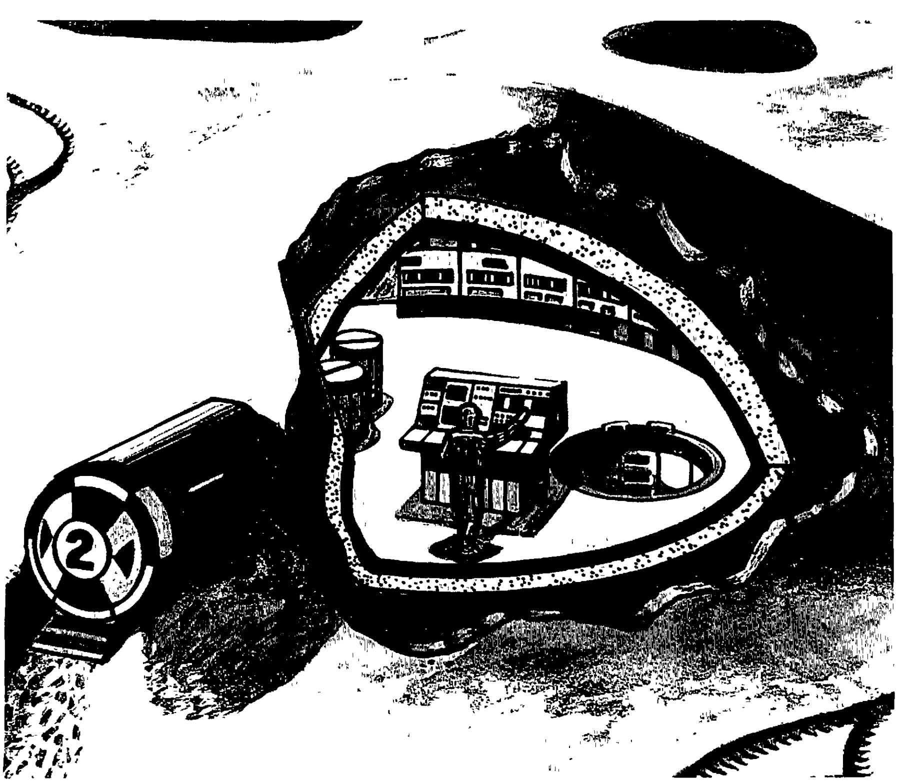


Figure 12

Lunar Base Control Room Made of Lunar Concrete

One use for concrete made primarily from lunar resources is seen in this cutaway sketch of a control room at a lunar base. Together with a blanket of lunar regolith, concrete would provide excellent shielding from the cosmic rays and solar flares that would be a serious hazard at a lunar base designed for long-term habitation. Such shielding could also be used to protect facilities in LEO or GEO.

resupply needs. At some point, local raw materials can be introduced into the cycle. This may be one of the first uses of lunar oxygen and of hydrogen implanted in lunar soil by the solar wind. Then, on a larger scale, lunar materials may be used as a substrate and nutrient source for agriculture. Asteroids can supply substances, such as carbon compounds and water, in which the Moon is deficient. Asteroidal water may be particularly valuable, if no ice is discovered on the Moon and if the hydrogen trapped in lunar soil proves to be impractical to utilize.

A more complete understanding of lunar and asteroidal resources will require additional exploration. Such exploration can be done without making any decision to commit to utilization of nonterrestrial resources and will provide important new data which will help in making such decisions. We therefore recommend that NASA's Office of Space Science and Applications (OSSA) and Office of Space Flight (OSF) jointly sponsor and conduct the study, analysis, and advocacy of two automated flight missions: a lunar polar geochemical orbiter and a near-Earth asteroid rendezvous, each having a combination of scientific and resource-exploration objectives. Both missions could use spacecraft similar to the Mars Observer now planned for launch in the early 1990s. Also, to evaluate the resource potential of Mars and its moons, Phobos and Deimos, we recommend that the Mars Observer data analysis be planned to include resource aspects, such as the potential for in situ propellant production.

Lunar resource exploration might proceed in one of three ways:

- A straight return by a human crew to a site on the Moon where features have been explored and sampled (such as that of Apollo 15, 16, or 17), with the intent of starting base buildup and resource utilization at that site; or
- Establishment of a prebase camp at some other site on the Moon, with the intent that humans would evaluate the local resources; or
- Conduct of an automated, mobile lunar surface exploration mission as a precursor to base siting.

Since strategy can be a function of the discoveries of a remote-sensing mission, we offer no recommendation regarding the choice among these options. We do, however, recommend that early lunar base plans allow for the possibility that any of the options might prove best.

Once serious planning for the use of a particular body of lunar material begins, it will be necessary to determine the extent of the potential mine in three dimensions. New instruments for probing to modest depths beneath the lunar surface may be required. We therefore recommend that limited-depth mapping be included among the objectives of any lunar surface exploration mission.

Asteroidal exploration might proceed by sending an automated lander and sample return mission to the most favorable near-Earth asteroid. The asteroid rendezvous would have to be preceded by an Earth-based search for the right asteroid. The search for near-Earth asteroids, and their characterization by remote sensing using ground-based telescopes, is a good example of a scientific activity with strong implications for the use of nonterrestrial resources. This work is now going on with a mixture of private and public support and could readily be accelerated at low cost.

Laboratory research, on a relatively small scale, using lunar simulants could yield fundamental knowledge important in choosing which technology to develop for the extraction of lunar oxygen, hydrogen, and metals. At similar levels, useful research could be done using meteorites to assess the technology needed to process asteroidal materials for water, carbon, nitrogen, and other volatiles. We recommend that NASA encourage such materials research.

It is a finding of the present study that the processing of nonterrestrial materials, though conceptually understood, has yet to be reduced to practice despite numerous past studies, recommendations, and even some laboratory work. In view of the long lead times characteristic of projects bringing new raw materials sources into production, we believe that more active preparations will soon be needed.

Though laboratory research in this area, as outlined above, is necessary, there are some processes that are ready for technology development and competitive evaluation at pilot-plant scale both on Earth and in space. A logical next step would be processing demonstrations at reduced gravity in the space station and ultimately on the Moon. An example of the needed technology would be a solar furnace designed to extract oxygen and structural materials from lunar soil on the surface of the Moon (see figure 8).

So much remains unknown about the behavior of the living systems (humans, microorganisms, plants, and animals) that will occupy the space habitats of the future that this is a research field with a very likely payoff. As in the case of inorganic materials, some aspects of this problem have already come past the research stage and are ready for technology development and evaluation. We recommend that NASA's Office of Aeronautics and Space Technology (OAST) support biotechnology work in two areas: (1) plant life support and intensive agriculture under simulated lunar conditions, leading to experimental demonstrations on a 1/6 *g* centrifuge in the space station, and (2) biological processing of natural raw materials, lunar and meteoritic, to concentrate useful substances (fig. 13). Some such techniques are already in use on a large scale in the mining industry on Earth.

Figure 13

Bacterial Processing of Metal Ores

Although most concepts of processing lunar and asteroidal resources involve chemical reactors and techniques based on industrial chemical processing, it is also possible that innovative techniques might be used to process such resources. Shown here are rod-shaped bacteria leaching metals from ore-bearing rocks through their metabolic activities. Bacteria are already used on Earth to help process copper ores. Advances in genetic engineering may make it possible to design bacteria specifically tailored to aid in the recovery of iron, titanium, magnesium, and aluminum from lunar soil or asteroidal regolith. Biological processing promotes the efficacy of the chemical processes in ore beneficiation (a synergistic effect).

Products derived from the processing of space resources will be used mainly or entirely in the space program itself, at least up to our reference date of 2010. Plans and methods should be developed with this in mind. We do not find any early application of nonterrestrial materials or products made from them on the surface of the Earth. Rather, these materials can accelerate progress at any given annual budget level and thus increase the space program's output of new information, which continues to be its main product.

We found that, while Mars and its moons (fig. 14) almost surely provide a large resource and thus offer the best prospects for sustained human habitation, the most likely use of martian resources would be local; that is, in support of martian exploration and settlement rather than for purposes elsewhere.

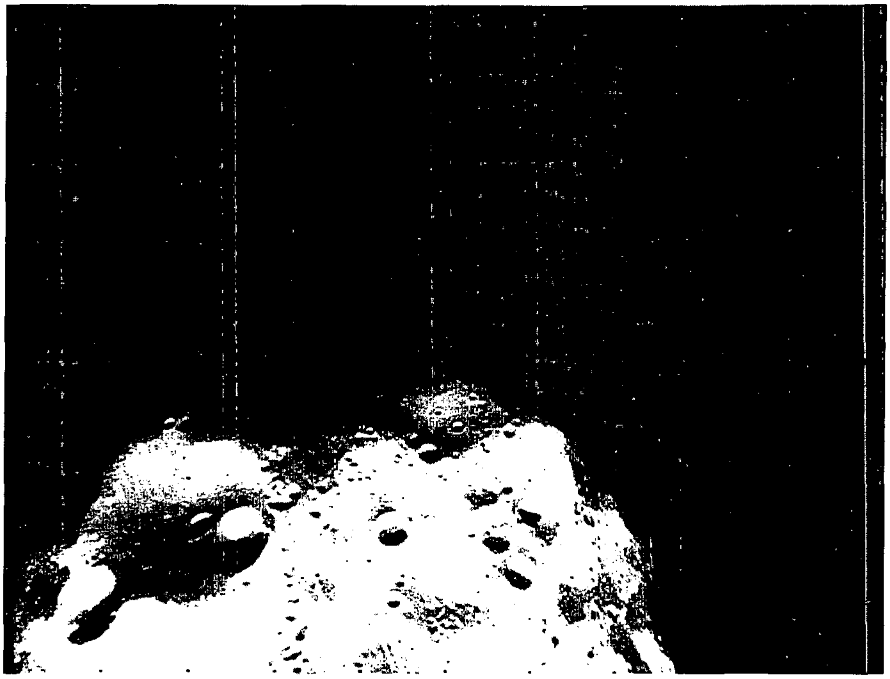


Figure 14

Phobos

One of the two moons of Mars, Phobos is slightly ellipsoidal, measuring about 25 km by 21 km. The surface of this moon is heavily cratered and grooved. The grooves may be the surface expressions of giant fractures in Phobos caused by an impact that nearly tore it apart and formed the large crater Stickney. The reflectivity of Phobos is similar to that of a type of asteroids that are thought by some to be made of carbonaceous chondrite material. If Phobos is indeed made of this material, it is likely to be rich in water and other volatiles. The loose, fine-grained regolith on the surface appears to be several hundred meters thick in places. This regolith might be relatively easy to mine and process for propellants such as oxygen and hydrogen. Metals might also be extracted from it. Similar techniques might be used to mine near-Earth asteroids for propellants or metals. These small bodies are of interest because less rocket energy is required to reach and return from some of them than is required to travel to the Moon and back.

CAPACITY 3
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Human and Social Concerns

Of all the natural resources in space, the most important in the long run will be the humans living there. Once working settlements (as distinct from expeditions) are established off the Earth, there will be opportunities for qualitative changes in human culture—in the space settlements and in the supporting communities on Earth.

Technologies must be developed to help people get into space, explore it, and live in it. And the use of nonterrestrial resources will affect the development of these technical changes. Agriculture is a clear example: until food production is achieved off Earth, human settlements will remain only outposts utterly dependent on resupply. Thus, the conversion of nonterrestrial materials into substrates for plant growth and the development of food plants usable off Earth will be primary needs.

More important, these technical changes can lead to cultural changes that will improve the quality of life for all space inhabitants. The United States and the Union of Soviet Socialist Republics are now taking the first steps toward permanent habitation of space. If this trend continues, it can divert some of both nations' high technology resources into efforts that are no threat to the people of Earth, and it can lead to the development of human courage, self-reliance, disciplined thinking, and new skills, on a scale otherwise known only in war. These human attributes can be the ultimate product of a program using what nature has provided off the Earth.

It appears likely that future projects will have large capital demands at the outset, large-scale management problems, and high risk both to capital and to national prestige. However, they may offer big economic rewards and many possible nonfinancial rewards, including extension of the human presence in space, development of new culture, and ultimately perhaps even favorable changes in the human species. We can expect scientific advances leading to greater technological excellence; the transfer of new ideas, knowledge, and technology to the Earth; new entrepreneurial horizons; the discovery of unpredicted resources; as well as unprecedented explorations and novel human experiences; opportunities for international cooperation; and the enhancement of American prestige and leadership.

Our central finding in this area is that, as the space program advances to a state where nonterrestrial resources can be used, its human aspects will become more and more important. The use of Earth's resources, both on land and on and under the sea, provides a clear example and suggests that many of these

Crisis at the Lunar Base

A projectile has penetrated the roof of one of the lunar base modules and the air is rapidly escaping. Three workers are trying to get into an emergency safe room, which can be independently pressurized with air. Two people in an adjoining room prepare to rescue their fellow workers. The remains of the projectile can be seen on the floor of the room. This projectile is probably a lunar rock ejected by a meteorite impact several kilometers from the base. A primary meteorite would likely be completely melted or vaporized by its high-velocity impact into the module, but a secondary lunar projectile would likely be going slowly enough that some of it would remain intact after penetrating the roof. Detailed safety studies are necessary to determine whether such a meteorite strike (or hardware failure or human error) is likely to create a loss-of-pressure emergency that must be allowed for in lunar base design. The presence of small safety chambers like this one would perhaps be useful as reassurance to lunar base occupants even though they were never actually used.

Artist. Pamela Lee

human problems—legal, political, environmental—will prove difficult and thus will demand early attention. Even if these problems are solved, there will remain substantial human problems within the program. Not only life support but also opportunities for the creative exercise of human talent off Earth must be provided if we are to reach a state where the use of nonterrestrial resources begins to yield a net gain to civilization.

We recommend that NASA encourage (and where possible sponsor) laboratory-scale research on the fundamentals of living systems, with the aim of improving the basis for choices in larger scale efforts such as the controlled ecological life support systems (CELSS) program and space station life support development. Habitat concepts should be studied, including resource substitutions and self-sufficiency to reduce resupply demand. In the specific context of this study, we recommend that this work consider the prospect of using lunar resources (both materials and environments) and asteroidal raw materials to support living systems on the Moon. Design studies should be made of generic human-machine systems adaptable to multiple locations off Earth and able to use local resources to the greatest extent feasible.

Robotics, automation, information, and communications—subjects already important in OAST's programs—will clearly be technologies both driven by and enabling the use of space resources. We recommend that OAST examine, and modify as appropriate, the ongoing NASA robotics, automation, information, and communications technology program in respect to those aspects affecting, or affected by, the use of nonterrestrial resources. An example could be the technology of lunar-surface-based teleoperators for mining and material transport.

Once people are established in low Earth orbit, a whole new field of engineering will begin to grow: operations centered off Earth. Experience with manned and automated operations controlled from centers on Earth shows that the operations discipline is a demanding and expensive one, often rivaling the hardware and other cost elements of a flight project and typically involving hundreds of skilled people acting in a carefully orchestrated manner. Technology can do much to reduce operations costs, but, even with Earth basing, realizing this potential has proved to be difficult. Advance simulations of space-based operations will probably pay dividends.

We recommend that OAST examine cost sources in present-day operations and investigate ways to reduce costs of space-based operations including mission control, maintenance and repair, refueling, and logistics and storage, using nonterrestrial resources where appropriate.

Basic research in support of the management of space-based operations should be carried out in biosocial systems, including general living systems research (see figure 15) and consideration of cognitive psychology, management science, the human migration process, and modes of human cooperation in space.

Funding for life support and general living systems research could be found at NASA's Office of Aeronautics and Space Technology (OAST), the National Science Foundation, the National Institutes of Health, the Environmental Protection Agency, and the Office of Naval Research. Ergonomics or human factors research could be funded by NASA OAST, the National Science Foundation, the National Institutes of Health, the Navy, Air Force, or Army, or the Department of Transportation. Space law and policy studies could be funded by the Law and Social Sciences Division of the National Science Foundation or the Office of Commercial Space Transportation of the Department of Transportation. Our point is that research on extended human presence in space requires expanded public and private support. Nationally, for example, other Government agencies beyond NASA should be investing in space R&D, as well as corporations and foundations outside the aerospace industry. International investment in such research is also in order.

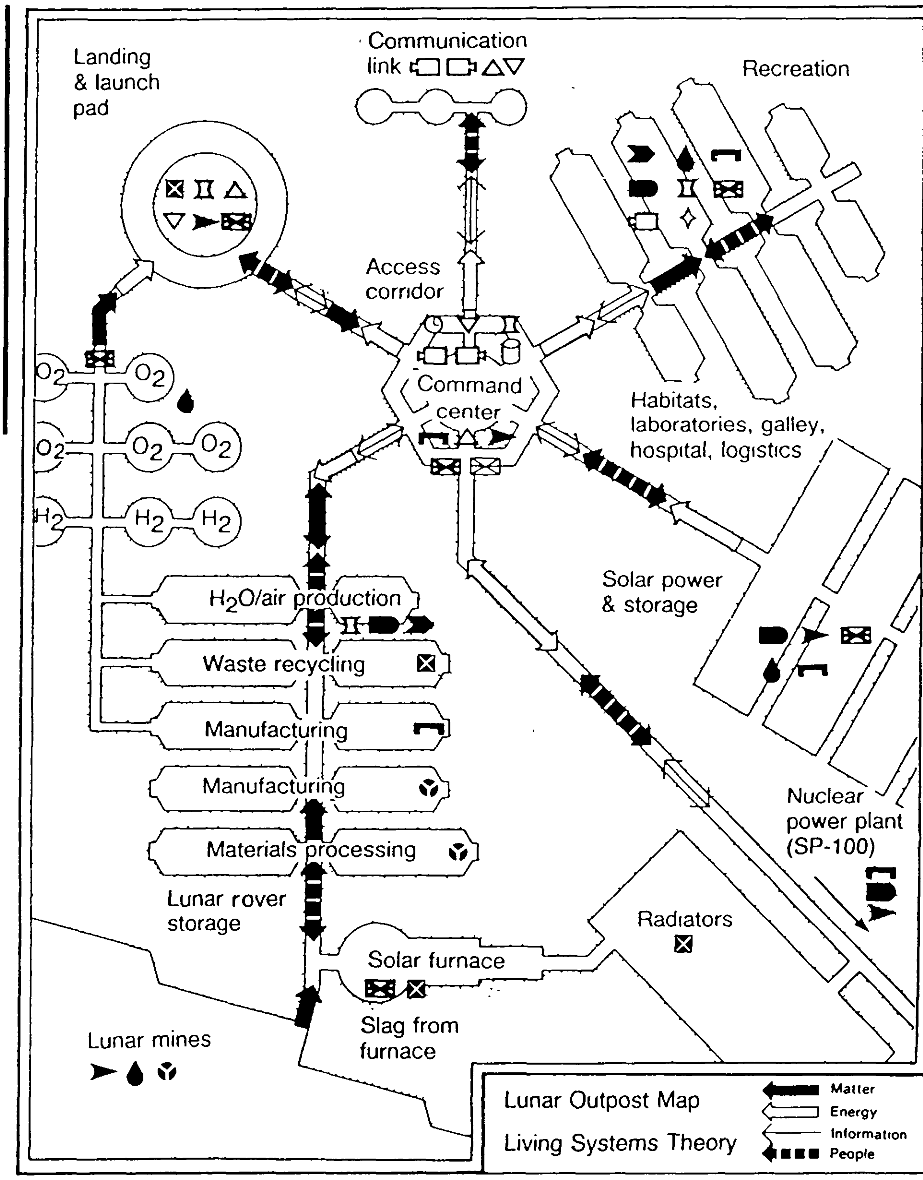

Communication link
Landing & launch pad
Recreation
Access corridor
O_2
H_2
Command center
Habitats, laboratories, galley, hospital, logistics
H_2O/air production
Waste recycling
Manufacturing
Manufacturing
Solar power & storage
Materials processing
Nuclear power plant (SP-100)
Lunar rover storage
Radiators
Solar furnace
Slag from furnace
Lunar mines
Lunar Outpost Map
Living Systems Theory
Matter
Energy
Information
People

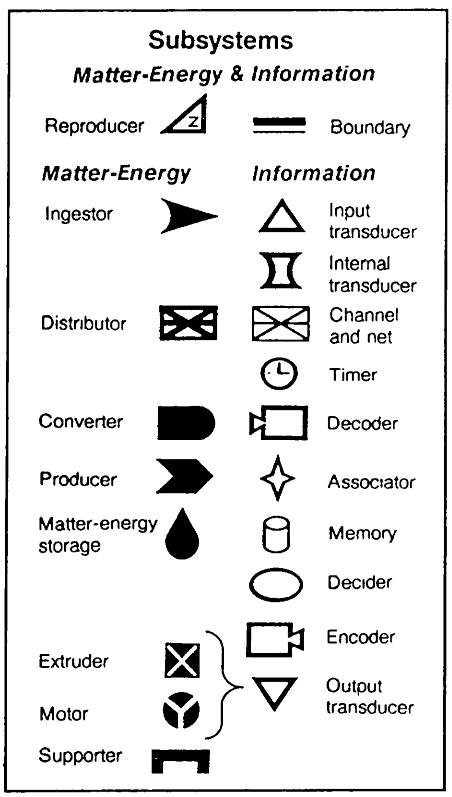
Figure 15

Lunar Outpost Map

General living systems theory and analysis constitutes a rational way to begin to understand the human factors which should guide all planning of space missions. This theory is a conceptual integration of biological and social approaches to the study of living systems. Living systems are open systems that input, process, and output matter and energy, as well as information which guides and controls all their parts. In human organizations, in addition to matter and energy flows, there are flows of personnel, which involve both matter and energy but also include information stored in each person's memory. There are two types of information flows in organizations: human and machine communications and money or money equivalents. Twenty subsystem processes dealing with these flows are essential for survival of systems at all levels.

General living systems theory has been applied in studying such organizations as corporations, military units, hospitals, and universities. It can similarly be applied in studying human settlements in space. The general procedure for analyzing such systems is to map them in two- or three-dimensional space. This map of a lunar outpost indicates its subsystems and the major flows within it. When these flows have been identified, gauges or sensors can be placed at various locations throughout the system to measure the rate of flow and provide information to each of the inhabitants and to others about the processes of the total system, so that its management can be improved (management information system) and its activities made not only more cost-effective but also more satisfying to the humans who live in it.

Such an analysis would take into account the primary needs of human systems—foraging for food and other necessary forms of matter and energy; feeding; fighting against environmental threats and stresses; fleeing from environmental dangers; and, in organizations which provide a comfortable, long-term habitat, perhaps reproducing the species. This study would analyze the effects on human social and individual behavior of such factors as weightlessness or 1/6 gravity; limited oxygen and water supplies; extreme temperatures; available light, heat, and power; varying patterns of light and dark; and so forth. A data bank or handbook could be developed of the values of multiple variables in each of the 20 subsystems of such a social system.



Economic, legal, political, international, and environmental aspects of a large and diverse space program using nonterrestrial resources require careful consideration.

The costs and benefits (both economic and nonfinancial) of programs utilizing nonterrestrial materials in space must be carefully analyzed. Detailed parametric models are needed which can be periodically updated as new data become available. Innovative means for financing such programs need to be found. Perhaps legislative initiatives should be taken to strengthen NASA's autonomy and enable the agency to enter into joint ventures with the private sector both here and abroad. We recommend continued exploration of new means for increasing nongovernmental participation in the space program, both to spread risks and costs and to broaden the advocacy base for a large space program benefiting from the use of resources off the Earth. Insurance for risk management and investment strategies for up-front capitalization should be examined.

We recommend exploration of ways to serve American national interests through either cooperative or competitive activities involving other nations in space. The relationship of the use of space resources to existing space treaties should be carefully examined.

Conclusion

It is our consensus that, after the space station becomes operational, any of several driving forces will result in an American initiative beyond LEO and GEO. That initiative might take any of several forms, but every scenario that we considered involves some combination of automated and human activities on the Moon. If a manned return to the Moon is chosen as a goal, then the prospect (and even the necessity) of using local resources arises. In this study we have examined some of the prospects for doing that, and we have recommended advance preparations toward the goal. These advance preparations are, in our judgment, practical and rewarding in proportion to their cost. We have identified places in existing Government organizations and programs where they could be carried out.

Because the Moon is believed to be deficient in some of the needed resources while meteorites are known to contain them, we have also recommended expansion and exploration of the known population of near-Earth asteroids, so that the role of this natural resource in space programs of the future can be properly evaluated. Also, we have noted the evidence that Mars and its satellites can provide local resources for missions there. We have not tried to predict just which objectives future Governments may aim toward. Instead, we have endeavored to define the nearer term technology measures that will be needed in any case and the nearer term flight projects which, if carried out, would broaden our understanding of the natural resources available in space.

Recommendations

Our main recommendations (unranked) are as follows:

- Include growth provisions in current space station and orbital transfer vehicle systems to enable them to evolve into a cislunar infrastructure.
- Conduct laboratory research and development on a variety of ways to process lunar and meteoritic materials and make useful products from them.
- Support planetary observer missions with objectives of gathering scientific information and exploring resources. Such missions might include
  - Lunar polar geochemical orbiter
  - Mars (and martian satellite) observer
  - Multiple near-Earth asteroid rendezvous
- Discover and characterize more near-Earth asteroids by Earth-based telescopic observations.
- Develop advanced propulsion technology to permit comparison and selection of systems for transport beyond Earth orbit.

- Continue closed-ecosystem research and development with the aim of reducing resupply transport demand.
- Expand research on the challenges of living off Earth, including habitat design, space ecology, human/machine interactions, human-rating of equipment, and human behavior in remote sites—physiological, psychological, and social.
- Emphasize physical experiments and hardware development in preference to more paper studies.

Not only should NASA increase funding in these areas, but also other funding sources, both public and private, should be explored for possible support of the recommended research. University and industrial foundations, private institutions such as the Space Studies Institute and the Planetary Society, and new entities such as space business enterprises all have sponsored small research efforts related to their interests and might do so in this case—if, and only if, the future importance of nonterrestrial resources is made credible.

We have, we believe, sketched a coherent program of activities, engaging the talents of Government, industry, and the research community, with an easily supportable initial funding level, that could gather essential knowledge and build advocacy for the day when Americans will once more bravely and confidently set out on voyages of discovery and settlement—this time to the Moon and beyond.

Addendum: Participants

The managers of the 1984 summer study were

David S. McKay, Summer Study Co-Director and Workshop Manager
Lyndon B. Johnson Space Center

Stewart Nozette, Summer Study Co-Director
California Space Institute

James Arnold, Director
of the California Space Institute

Stanley R. Sadin, Summer Study Sponsor
for the Office of Aeronautics and Space Technology
NASA Headquarters

Those who participated in the 10-week summer study as faculty fellows were the following:

James D. Burke	Jet Propulsion Laboratory
James L. Carter	University of Texas, Dallas
David R. Criswell	California Space Institute
Carolyn Dry	Virginia Polytechnic Institute
Rocco Fazzolare	University of Arizona
Tom W. Fogwell	Texas A & M University
Michael J. Gaffey	Rensselaer Polytechnic Institute
Nathan C. Goldman	University of Texas, Austin
Philip R. Harris	California Space Institute
Karl R. Johansson	North Texas State University
Elbert A. King	University of Houston, University Park
Jesa Kreiner	California State University, Fullerton
John S. Lewis	University of Arizona
Robert H. Lewis	Washington University, St. Louis
William Lewis	Clemson University
James Grier Miller	University of California, Los Angeles
Sankar Sastri	New York City Technical College
Michele Small	California Space Institute

Participants in the 1-week workshops included the following:

Constance F. Acton	Bechtel Power Corp.
William N. Agosto	Lunar Industries, Inc.
A. Edward Bence	Exxon Mineral Company
Edward Bock	General Dynamics
David F. Bowersox	Los Alamos National Laboratory
Henry W. Brandhorst, Jr.	NASA Lewis Research Center
David Buden	NASA Headquarters
Edmund J. Conway	NASA Langley Research Center
Gene Corley	Portland Cement Association
Hubert Davis	Eagle Engineering
Michael B. Duke	NASA Johnson Space Center
Charles H. Eldred	NASA Langley Research Center
Greg Fawkes	Pegasus Software
Ben R. Finney	University of Hawaii
Philip W. Garrison	Jet Propulsion Laboratory
Richard E. Gertsch	Colorado School of Mines
Mark Giampapa	University of Arizona
Charles E. Glass	University of Arizona
Charles L. Gould	Rockwell International
Joel S. Greenberg	Princeton Synergetics, Inc.
Larry A. Haskin	Washington University, St. Louis
Abe Hertzberg	University of Washington
Walter J. Hickel	Yukon Pacific
Christian W. Knudsen	Carbotek, Inc.
Eugene Konecci	University of Texas, Austin
George Kozmetsky	University of Texas, Austin
John Landis	Stone & Webster Engineering Corp.
T. D. Lin	Construction Technology Laboratories
John M Logsdon	George Washington University
Ronald Maehl	RCA Astro-Electronics
Thomas T. Meek	Los Alamos National Laboratory
Wendell W. Mendell	NASA Johnson Space Center
George Mueller	Consultant
Kathleen J. Murphy	Consultant
Barney B. Roberts	NASA Johnson Space Center
Sanders D. Rosenberg	Aerojet TechSystems Company
Robert Salkeld	Consultant
Donald R. Saxton	NASA Marshall Space Flight Center
James M. Shoji	Rockwell International
Michael C. Simon	General Dynamics
William R. Snow	Electromagnetic Launch Research, Inc.
Robert L. Staehle	Jet Propulsion Laboratory
Frank W. Stephenson, Jr.	NASA Headquarters
Wolfgang Steurer	Jet Propulsion Laboratory
Richard Tangum	University of Texas, San Antonio
Mead Treadwell	Yukon Pacific
Terry Triffet	University of Arizona
J. Peter Vajk	Consultant
Jesco von Puttkamer	NASA Headquarters
Scott Webster	Orbital Systems Company
Gordon R. Woodcock	Boeing Aerospace Company

The following people participated in the summer study as guest speakers and consultants:

Edwin E. "Buzz" Aldrin	Research & Engineering Consultants
Rudi Beichel	Aerojet TechSystems Company
David G. Brin	California Space Institute
Joseph A. Carroll	California Space Institute
Manuel I. Cruz	Jet Propulsion Laboratory
Andrew H. Cutler	California Space Institute
Christopher England	Engineering Research Group
Edward A. Gabris	NASA Headquarters
Peter Hammerling	LaJolla Institute
Eleanor F. Helin	Jet Propulsion Laboratory
Nicholas Johnson	Teledyne Brown Engineering
Joseph P. Kerwin	NASA Johnson Space Center
Joseph P. Loftus	NASA Johnson Space Center
Budd Love	Consultant
John J. Martin	NASA Headquarters
John Meson	Defense Advanced Research Projects Agency
Tom Meyer	Boulder Center for Science and Policy
John C. Niehoff	Science Applications International
Tadahiko Okumura	Shimizu Construction Company
Thomas O. Paine	Consultant
William L. Quaide	NASA Headquarters
Namika Raby	University of California, San Diego
Donald G. Rea	Jet Propulsion Laboratory
Gene Roddenberry	Writer
Harrison H. "Jack" Schmitt	Consultant
Richard Schubert	NASA Headquarters
Elie Shneour	Biosystems Associates, Ltd.
Martin Spence	Shimizu Construction Company
James B. Stephens	Jet Propulsion Laboratory
Pat Sumi	San Diego Unified School District
Robert Waldron	Rockwell International
Simon P. Worden	Department of Defense
William Wright	Defense Advanced Research Projects Agency

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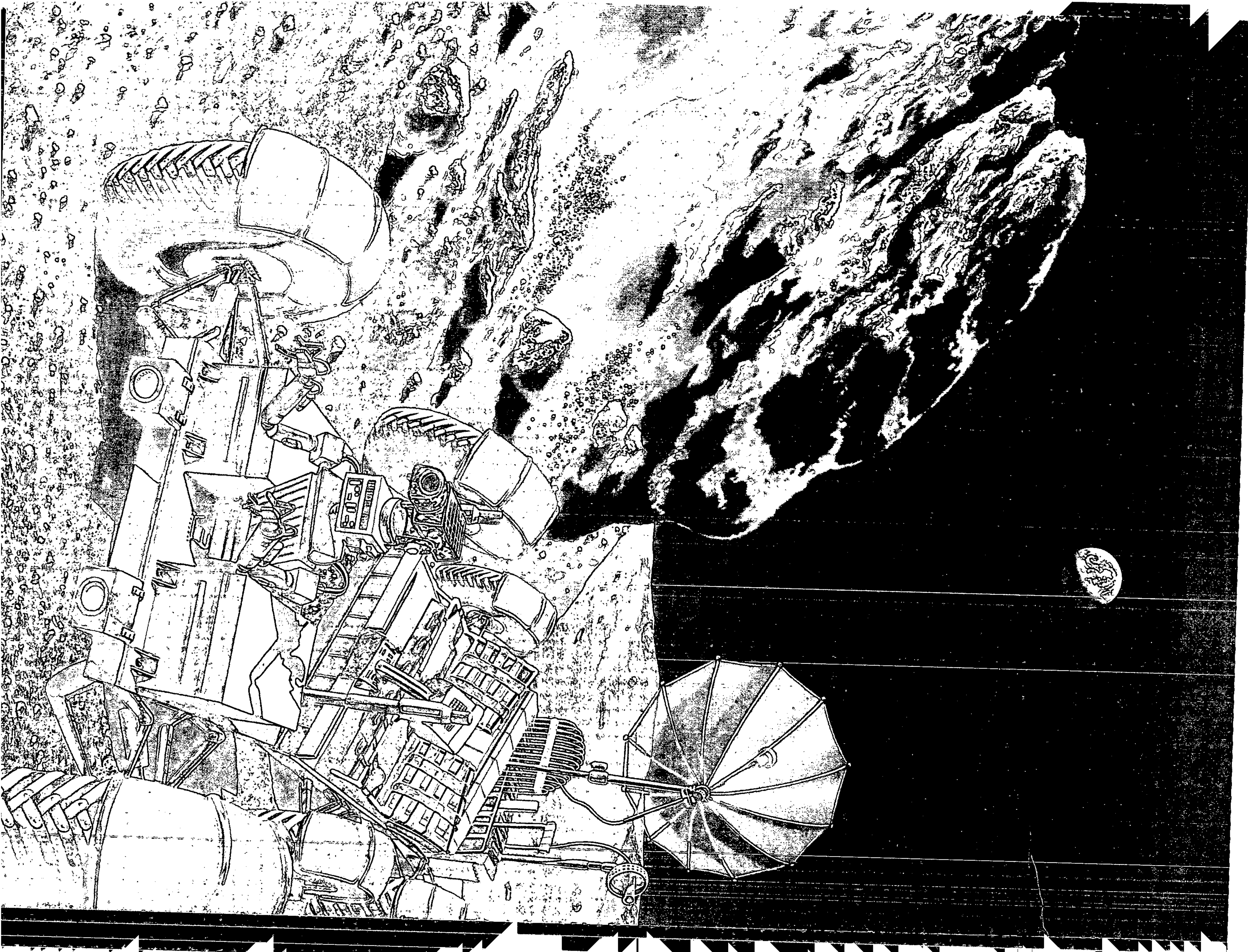
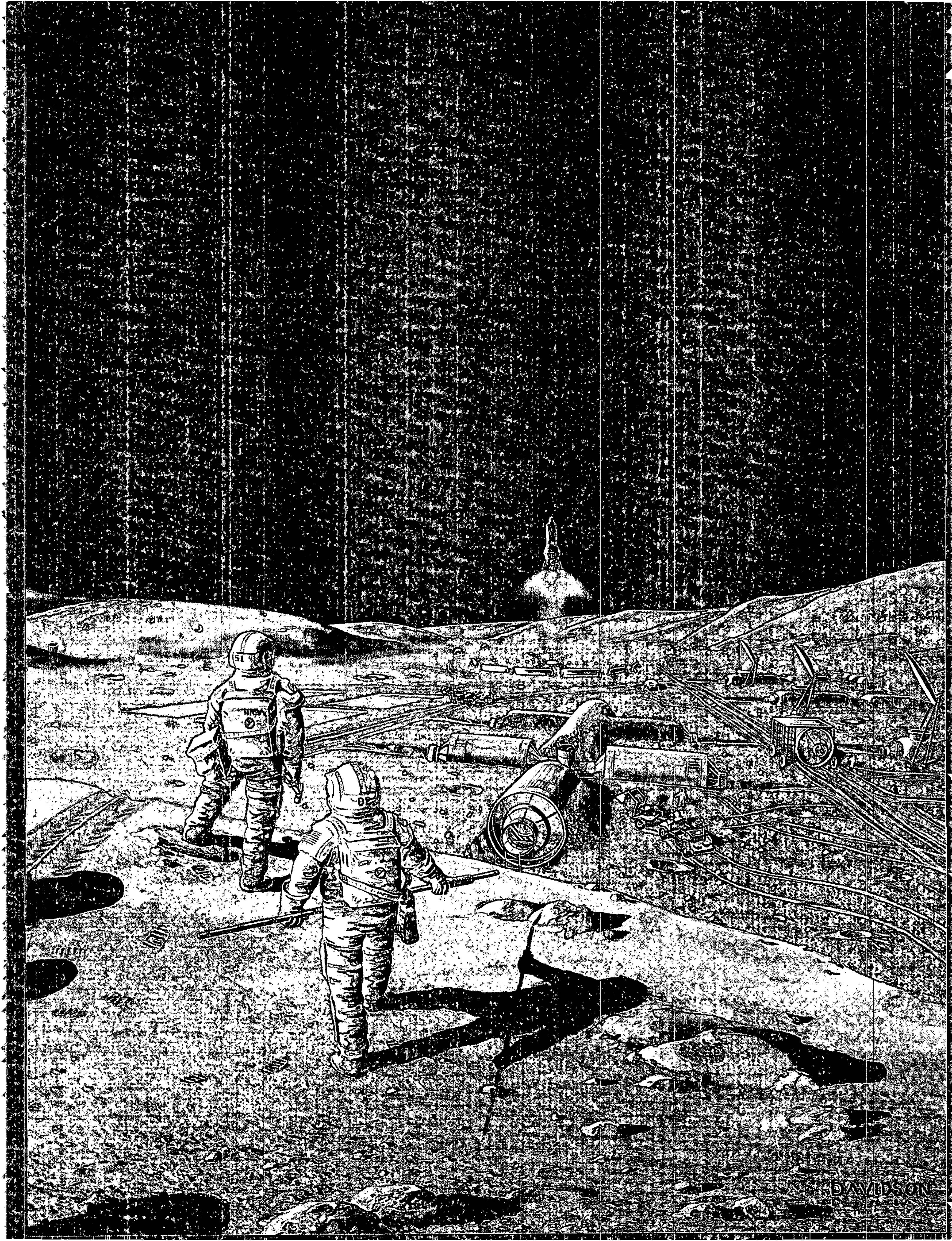
SPACE RESOURCES

Scenarios




DAVIDSON

Frontispiece

Advanced Lunar Base

In this panorama of an advanced lunar base, the main habitation modules in the background to the right are shown being covered by lunar soil for radiation protection. The modules on the far right are reactors in which lunar soil is being processed to provide oxygen. Each reactor is heated by a solar mirror. The vehicle near them is collecting liquid oxygen from the reactor complex and will transport it to the launch pad in the background, where a tanker is just lifting off. The mining pits are shown just behind the foreground figure on the left. The geologists in the foreground are looking for richer ores to mine.

Artist: Dennis Davidson

Space Resources

Scenarios

Editors

Mary Fae McKay, David S. McKay, and Michael B. Duke

Lyndon B. Johnson Space Center Houston, Texas

1992

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Preface

Space resources must be used to support life on the Moon and exploration of Mars. Just as the pioneers applied the tools they brought with them to resources they found along the way rather than trying to haul all their needs over a long supply line, so too must space travelers apply their high technology tools to local resources.

The pioneers refilled their water barrels at each river they forded; moonbase inhabitants may use chemical reactors to combine hydrogen brought from Earth with oxygen found in lunar soil to make their water. The pioneers sought temporary shelter under trees or in the lee of a cliff and built sod houses as their first homes on the new land; settlers of the Moon may seek out lava tubes for their shelter or cover space station modules with lunar regolith for radiation protection. The pioneers moved further west from their first settlements, using wagons they had built from local wood and pack animals they had raised; space explorers may use propellant made at a lunar base to take them on to Mars.

The concept for this report was developed at a NASA-sponsored summer study in 1984. The program was held on the Scripps campus of the University of California at San Diego (UCSD), under the auspices of the American Society for Engineering Education (ASEE). It was jointly managed by the California Space Institute and the Lyndon B. Johnson Space Center, under the direction of the Office of Aeronautics and Space Technology (OAST) at NASA Headquarters. The study participants (listed in the addendum) included a group of 18 university teachers and researchers (faculty fellows) who were present for the entire 10-week period and a larger group of attendees from universities, Government, and industry who came for a series of four 1-week workshops.

The organization of this report follows that of the summer study. *Space Resources* consists of a brief overview and four detailed technical volumes: (1) Scenarios; (2) Energy, Power, and Transport; (3) Materials; (4) Social Concerns. Although many of the included papers got their impetus from workshop discussions, most have been written since then, thus allowing the authors to base new applications on established information and tested technology. All these papers have been updated to include the authors' current work.

In this *Scenarios* volume, a number of possible future paths for space exploration and development are presented. The paths set the scene for the more detailed discussion in the remaining volumes of the issues of power and transport, nonterrestrial materials, and human considerations.

This is certainly not the first report to urge the utilization of space resources in the development of space activities. In fact, *Space Resources* may be seen as the third of a trilogy of NASA Special Publications reporting such ideas arising from similar studies. It has been preceded by *Space Settlements: A Design Study* (NASA SP-413) and *Space Resources and Space Settlements* (NASA SP-428).

And other, contemporaneous reports have responded to the same themes. The National Commission on Space, led by Thomas Paine, in *Pioneering the Space Frontier*, and the NASA task force led by astronaut Sally Ride, in *Leadership and America's Future in Space*, also emphasize expansion of the space infrastructure; more detailed exploration of the Moon, Mars, and asteroids; an early start on the development of the technology necessary for using space resources; and systematic development of the skills necessary for long-term human presence in space.

Our report does not represent any Government-authorized view or official NASA policy. NASA's official response to these challenging opportunities must be found in the reports of its Office of Exploration, which was established in 1987. That office's report, released in November 1989, of a 90-day study of possible plans for human exploration of the Moon and Mars is NASA's response to the new initiative proposed by President Bush on July 20, 1989, the 20th anniversary of the Apollo 11 landing on the Moon: "First, for the coming decade, for the 1990s, Space Station *Freedom*, our critical next step in all our space endeavors. And next, for the new century, back to the Moon, back to the future, and this time, back to stay. And then a journey into tomorrow, a journey to another planet, a manned mission to Mars." This report, *Space Resources*, offers substantiation for NASA's bid to carry out that new initiative.

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Introduction

James D. Burke and Barney B. Roberts

A major objective of this workshop was to develop scenarios for NASA's advanced missions. The first scenario, business as usual, we labeled the "NASA baseline plan." It shows the expected development of NASA programs under existing budget trends. We developed two, more aggressive scenarios that would require funding above the steady-state budget projection. These scenarios were built on the assumption that significant nonterrestrial resources would be available. The workshop then sought to identify additional technologies that would support the alternative scenarios.

In proposing alternative scenarios, we debated what goals were most promising or would have the most public support. It was apparent that limiting the concept of space resources to tangible materials from the Moon or asteroids could fail to support many popular space initiatives, such as a manned Mars mission, significant commercial applications in low Earth orbit (LEO) or geosynchronous Earth orbit (GEO), and tourism. Thus, although the general thrust of the alternative scenarios was toward the utilization of nonterrestrial resources, one scenario emphasized the Moon ("space resource utilization") and the other was more general ("balanced infrastructure buildup").

To avoid being short-sighted on the subject of space resources, the workshop expanded its list to include such items as vacuum, low gravity, and location/view. We also note that our more complete list might not exhaust the possibilities.

Once these points were agreed upon, the workshop divided the analysis and reporting tasks among its members. The contributed sections discuss the baseline scenario, generic alternatives, potential sociopolitical conditions, the common or nodal technologies required to support the alternative scenarios, and issues for further study.

Baseline Program

Barney B. Roberts and Jesco von Puttkamer

Assumptions

The workshop agreed to use a proposed NASA plan as the baseline program. This assumed program has been developed from several sources of information and is extrapolated over future decades using a set of reasonable assumptions based on incremental growth. The principal source of basic data was a presentation given to the workshop by Jesco von Puttkamer, representing NASA's advanced planning activities. This work shows the space program planning efforts divided into four domains (fig. 1). Future activities are planned with balanced emphasis among these four domains.

It was considered reasonable to assume that the level of activity would remain constant in order to stabilize the use of public resources. This assumption resulted in a sequence of programs with waxing and waning budget requirements. As one program decreases in construction and development costs and becomes operational, public resources are made available for the next program. This approach levels the impact on facilities and capital investments and maintains a skilled and experienced work force.

As for budget estimates, only low to moderate growth after adjustment for inflation was assumed. A key principle underlying the proposed program is that maximum benefits will be obtained from commonality and subsystem evolution. Technologies and program elements will be synergistic and integrated to allow one project to use capabilities developed by another. In addition, the NASA planners tried to make realistic and practical estimates of the technology developments required to support each phase of design and construction. Using this information and previous history on the programmatics involved in the development of space hardware, NASA constructed a phased, evolutionary set of scenarios that we consider reasonable.

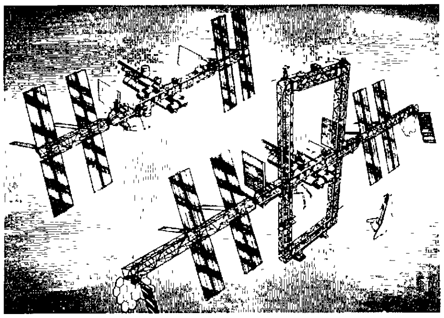
To summarize, the assumptions for the NASA baseline program are as follows:

- Balanced emphasis in four domains
- Constant level of activity
- Low to moderate real budget growth
- Maximum use of commonality
- Realistic and practical technology development

Figure 1

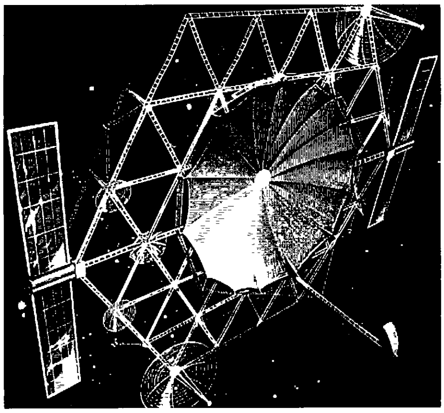
NASA's Advanced Planning

NASA is planning a balanced program, with roughly equal emphasis given to each of four domains. The first domain is low Earth orbit (LEO). Activities there are concentrated on the space station but extend on one side to Earth-pointing sensors from unmanned platforms and on the other to the launch and staging of unmanned solar system exploration missions. The second domain is geosynchronous Earth orbit (GEO) and cislunar space. Activities there include all GEO missions and operations, both unmanned and manned, and all transport of materials and crews between LEO and the vicinity of the Moon. The third domain is the Moon itself. Lunar activities are to include both orbiting and landing missions; the landings may be either unmanned or manned. The last domain is Mars. Missions to Mars will initially be unmanned but they will eventually be manned.



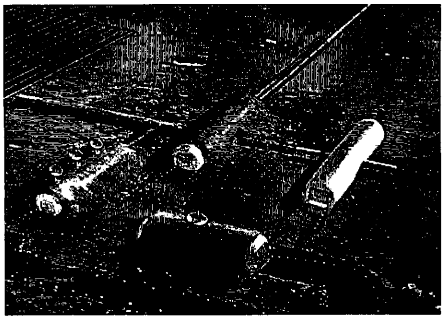
(1) LEO Space Station

Although the Soviets have had cosmonauts continuously occupying their Mir spacecraft for some time, the U.S. space station will be the first permanently occupied space outpost in the American space program. The space station will be the location for a variety of Earth observations and for many scientific and engineering experiments in microgravity. It will also be a transportation node and servicing center for satellites and space vehicles.



(2) GEO Platform

Location in geosynchronous orbit is required for most types of communication satellites. Because this orbit is filling up, a trend may develop to cluster multiple users on a single platform. The large platform shown in this drawing contains about a dozen separate antennas, each of which can be aimed at a different user. To be cost-effective, such large platforms must be able to be serviced and repaired. For service and repair, either the entire platform must be returned to the space station by orbital transfer vehicle or astronauts must travel to geosynchronous orbit for onsite maintenance



(3) Spartan Lunar Base

The early lunar base may consist of several modules similar to habitation and laboratory modules for the space station, which can be transported to the lunar surface and covered with lunar regolith for radiation protection. In some scenarios, the early lunar base would be totally dependent on transport from Earth for all supplies and consumables. In other scenarios, a small plant would be emplaced, which would allow the production of oxygen for life support.

(4) Closeup of the Surface of Mars From the Unmanned Viking Lander

While Viking provided spectacular pictures of the surface of Mars and some chemistry data for the two lander sites, an indepth understanding of martian samples and the detailed data necessary to describe the evolution of Mars (age dating, mineralogy, possible fossils) can be gained only from actual samples of rocks and soil returned to Earth for detailed analysis using sophisticated laboratory instruments.

American Station at the South Pole

The station consists of several buildings within a large-diameter (approximately 100-meter) geodesic dome. The buildings include laboratories, service areas, and habitation modules. This station is probably the closest thing we have to a base on another planet. The South Pole station is continuously occupied, but crewmembers arrive or depart only during the summer season. While the occupants can venture outside with protective clothing ("space suits") during the winter, they are mostly dependent on the shelter provided by the geodesic dome and the buildings within the dome, much as they would be at a Moon or Mars base. Most of the supplies must be brought in by air, but some use is made of local resources. Local ice is used for water, and, of course, local oxygen is used for breathing and as an oxidizer for combustion, including operation of internal combustion engines.

Photo. Michael E. Zolensky

Program Elements and Descriptions

The first domain shown in figure 1 (LEO) emphasizes the space station and includes the recommended program of the Solar System Exploration Committee (SSEC), Earth observation satellites, manufacturing in low Earth orbit, and other commercial ventures such as tourism. The second domain (GEO) emphasizes commercial activities in geosynchronous orbit–mostly communication satellites or platforms. Other GEO facilities would include an experimental platform and later a manned "shack" to support and maintain the GEO facilities.

The third domain (the Moon) consists of the establishment of a temporarily manned science and research camp, similar to an Antarctic outpost. The lunar base would be totally dependent on Earth-supplied consumables and transportation. The fourth domain (Mars) includes an unmanned sample return mission.

Folding these four domains into a baseline program in accordance with the above assumptions results in the plan depicted in figure 2.

Critiques of the NASA Baseline

The workshop participants offered some critiques of the baseline plan, which are documented in this subsection in order to use them in the next section on alternative scenarios.

1. *Critique:* Devote more emphasis to asteroids as a source of nonterrestrial resources.

   Rebuttal: Resources on the Moon may be more limited than those of asteroids; however, the high leverage items such as oxygen for transportation and mass for shielding are available there, and the Moon has many other advantages to science and human presence that asteroids may be lacking.

   Resolution: Seriously consider asteroids as a viable source of resources in conjunction with other potential sources.

2. *Critique:* The baseline program demonstrates a lack of vision which is a result of conservative budget requests (or vice versa).

   Rebuttal: NASA is aggressive in its budget submittals and is

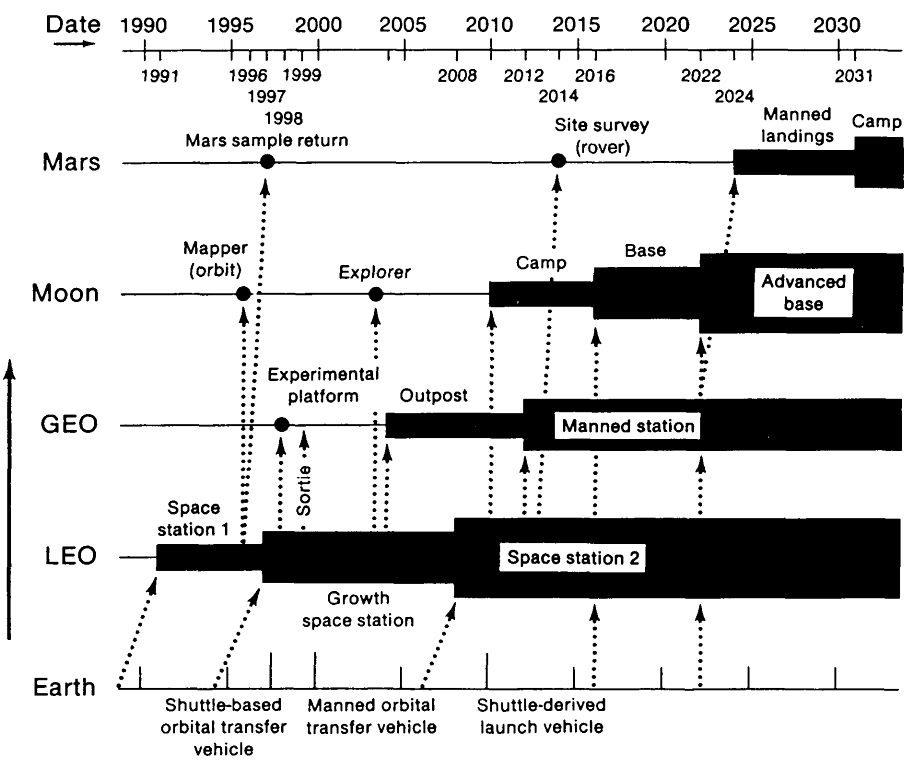


Figure 2

Baseline Scenario

If NASA continues its business as usual without a major increase in its budget and without using nonterrestrial resources as it expands into space, this is the development that might be expected in the next 25 to 50 years. The plan shows an orderly progression in manned missions from the initial space station in low Earth orbit (LEO) expected in the 1990s, through an outpost and an eventual space station in geosynchronous Earth orbit (GEO) (from 2004 to 2012), to a small lunar base in 2016, and eventually to a Mars landing in 2024. Unmanned precursor missions would include an experiment platform in GEO, lunar mapping and exploration by robot, a Mars sample return, and an automated site survey on Mars. This plan can be used as a baseline scenario against which other, more ambitious plans can be compared.

demonstrably second only to the Department of Defense (DOD) in budget growth. However, the fact remains that policy guidelines established by the Administration and Congress do not permit much more than the proposed baseline.

Resolution: A small portion of the planning exercise should not constrain itself within budget limitations but direct its attention to truly visionary space objectives in order to have an impact on our near-term technology developments and thereby contribute constructively to future budget drafts. NASA needs to make a better effort to "sell" its proposed programs to Congress and to the public.

3. *Critique:* The NASA baseline plan should be compressed in time to allow an earlier start on some selected programs.

   Rebuttal: An unlimited budget cannot resolve all problems involving the factor of time. Technology developments require significant time for resolution even when adequately funded. In addition, the technology developed for each new program feeds on or evolves from the technology developed for a precursor program.

   Resolution: Identify key technologies for early development and, where possible and practical, compress schedules.

Alternative Scenarios Utilizing Nonterrestrial Resources

Charles H. Eldred and Barney B. Roberts

This section of the report provides a collection of alternative scenarios that are enabled or substantially enhanced by the utilization of nonterrestrial resources. Here we take a generalized approach to scenario building so that our report will have value in the context of whatever goals are eventually chosen.

One significant finding of this workshop is that to discuss only tangible materials from asteroids or the lunar surface is probably too limiting an assumption to permit consideration of all viable scenarios. Thus, although we decided to discuss the following space resources, we realize that this list is nonexhaustive.

- Tangible materials
  - Lunar
  - Asteroidal
  - Martian
- Vacuum
- Energy
- Low to negligible gravity
- Physical location/view

The following paragraphs will discuss, in varying detail, each of these resources.

Space Resources

Tangible Materials

Lunar materials: The foremost lunar resource we identified was lunar oxygen for rocket propulsion (see fig. 3). The Moon can also

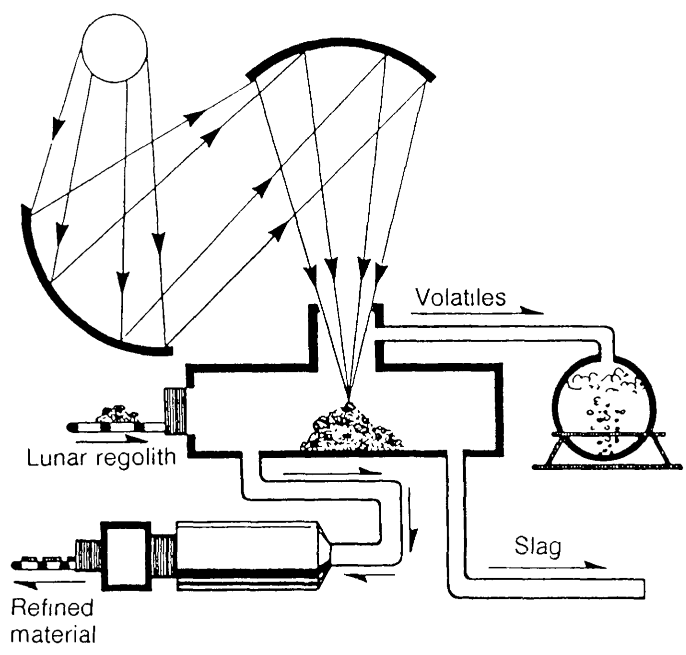


Figure 3

Lunar Materials Processing

This schematic drawing shows three main classes of products (volatiles, metals, bulk construction material) which can be made from lunar raw material. Lunar regolith is carried by a conveyor belt into a reactor, where it is heated by concentrated solar energy. Simple heating will cause it to release trapped solar wind volatiles, including hydrogen and rare gases. If it is heated in an atmosphere rich in hydrogen or another reductant, chemical reduction will take place, causing the lunar material to release oxygen from oxides and silicates. When sufficient oxygen is released, some of the reduced metals formed by the process can be refined and formed into ingots or cast into useful shapes. The remaining material can be withdrawn as slag, which can be used for construction of buildings and roads or as radiation shielding.

be a source of metals (iron, aluminum, magnesium, titanium) and nonmetals (glass, ceramics, concrete), which may find use as structural or shielding materials on and off the Moon. The Moon is relatively deficient in some of the more volatile elements–hydrogen, carbon, and nitrogen.

Asteroidal materials: Earth-approaching asteroids are rocky bodies that can provide useful materials, including some elements not found in abundance on the Moon. Some asteroids contain substantial quantities of water and carbonaceous material; others have abundant metal, including iron, nickel, cobalt, and the platinum group (see fig. 4). Some asteroids are energetically more accessible than the lunar surface; however, trip times are generally long and low-energy opportunities limited. For this reason, these asteroids don't offer convenient staging points.

Martian materials: The utilization of martian resources, particularly to produce propellants, is a probable aspect of an intensive Mars exploration program. Propellants could be extracted from Mars' atmosphere or from materials on the surface of Mars, Phobos, or Deimos (see fig. 5). These satellites have characteristics of carbonaceous asteroids and for many purposes, including access, may be considered as asteroids.

Vacuum

Vacuum, used in many scientific experiments and manufacturing processes, is expensive to create and limited in volume on Earth. Workshop participants were not convinced that going into space to utilize the vacuum would lead to

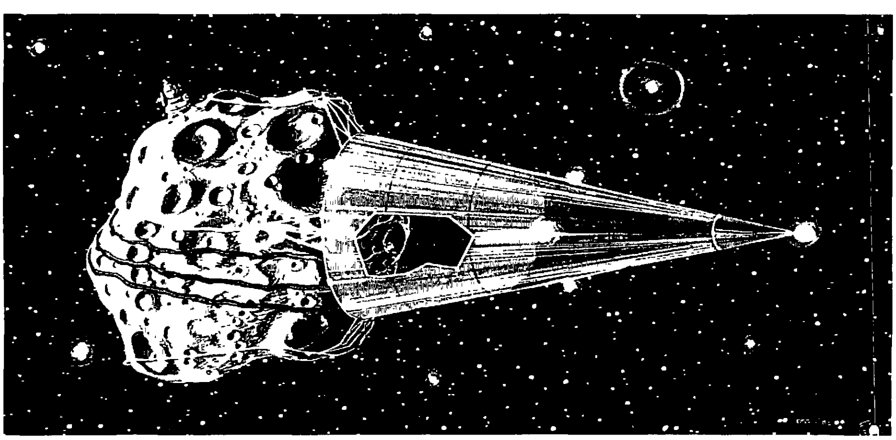


Figure 4

Mining an Asteroid

Mining asteroids will be a major technological challenge. Here is one concept in which a robot mining vehicle with paddle wheels moves around the surface of the asteroid and throws out material, which is caught in the cone-shaped catcher attached to the asteroid with cables. When it is full, attached thrusters will propel the catcher back to near-Earth space, where the asteroidal ore can be processed for water, carbonaceous materials, and metals.

economic benefits, considering the high cost of space transportation today. However, the potential of the limitless vacuum available in space kept it on the list as a viable resource. The unlimited vacuum could enable new analytical or testing procedures that depend on the surface properties of materials or the transmission of molecular beams. The vacuum of space could enable accelerators with no need, or a substantially reduced need, for containment devices. Such vacuum might permit new uses of the metals sodium and potassium, which are difficult to handle in the Earth's atmosphere. And it could allow the high-temperature vacuum processing of glasses, metals, and cement.

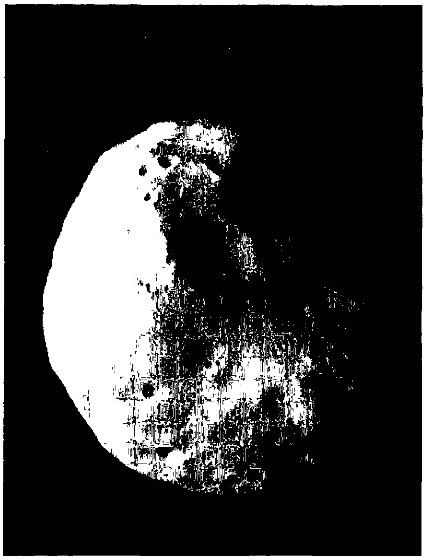


Figure 5

Phobos

Phobos, one of the two moons of Mars, is a likely target for any future martian missions. Phobos is 27 by 19 km and has a relatively low density of 1 9 gm/cm^3. The escape velocity from Phobos is only 11 m/sec. The optical properties of Phobos are similar to those of a type of asteroids that are thought by many to be of carbonaceous chondrite composition. Phobos has a well-developed groove structure, which may reflect major internal fracturing originating from large impacts. Phobos is inside the Roche limit for Mars and is being pulled even closer by tidal forces. Within about 50 million years, Phobos will be completely torn apart by these tidal forces and will become a ring around Mars.

Energy

Energy from space has been of practical use for many years. The primary energy source is of course the Sun. The most prominent application is solar photovoltaic power for satellites now in orbit. In the state-of-the-art process, solar cells directly convert incident solar energy into electrical energy. The advantages of collecting solar energy in space rather than on Earth arise principally from two facts: The first is that one can get more solar energy by choosing an orbit that has more "daylight" hours, and the second is that one can avoid interference from the atmosphere.

Energy from space may be utilized in space to power facilities (including those on the surfaces of planetary bodies) or can be returned to Earth for conversion to electrical energy. Alternatively, the Sun's energy may be used directly. The propulsive power of solar photons may be used to drive a solar sail. Direct use of thermal energy to provide process heat may be important in space. The Sun's light could be reflected, selectively, to the Earth to light cities, agricultural areas, or arctic night operations (see fig. 6).

Large space facilities, such as the space station or a lunar base, will

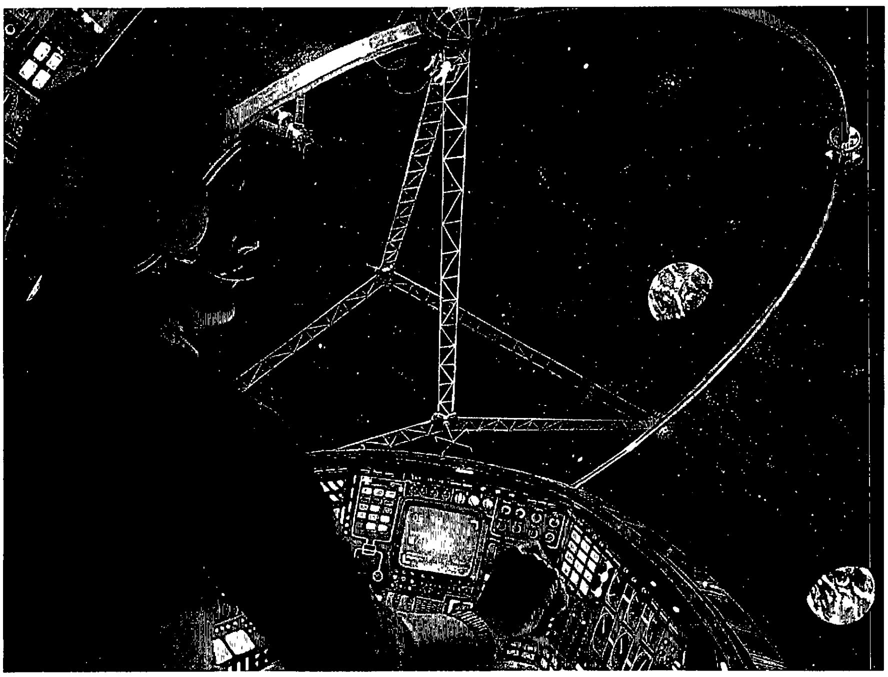


Figure 6

Reflected Sunlight Illuminates the Earth

In a simple example of how solar energy from space might be useful, large-diameter mirrors provide illumination where needed on Earth. In this concept, a mirror, 300 meters in diameter, made of thin Mylar film and supported by a ring and girder structure, is being set up in geosynchronous orbit. Such mirrors would provide nighttime illumination equivalent to full moonlight for any area about 300 km in diameter. A number of mirrors could be pointed at the same area to provide much brighter illumination. This illumination might be useful for lighting cities, agricultural areas, or arctic night operations. Other potential uses are to light up a disaster area or an area undergoing a power blackout.

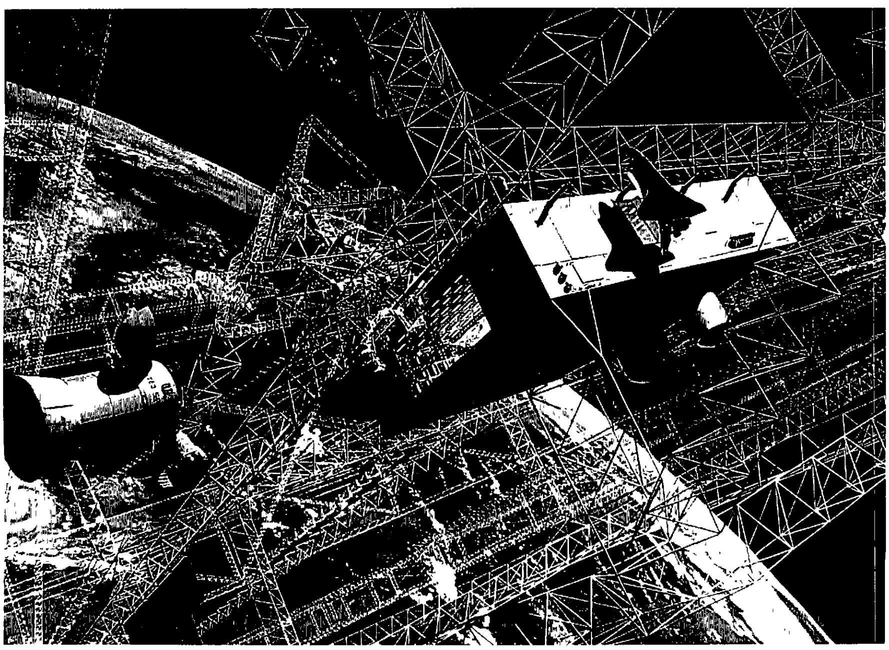


Figure 7

Construction of a Large Solar Power Station

In the future, large structures built in space may include solar power stations that will collect solar power using photovoltaic arrays. This power could be used in advanced space stations or beamed to a lunar base by microwave. In this view, a framework for such a station is being constructed. The station includes a service and equipment bay, in which subcomponents can be assembled, tested, and repaired.

Artist: John J. Olson

require significant power (see fig. 7). The power requirements for the current space station configuration are so large that the structural design and control system requirements will be driven by the solar panels if photovoltaic devices are used. A competing design concept being considered is solar dynamic (see fig. 8). This approach would use an energy-focusing mirror and a heat engine to drive a generator. Another approach would use electrodynamic tethers to exchange orbital energy for electrical energy. This very efficient process may be useful in low Earth orbit for energy storage but could not produce the high power levels needed for the primary supply system.

Several NASA and privately funded efforts have been undertaken to define ways in which space-supplied energy might be used to replace energy from nonrenewable Earth-based resources. One of these was the solar power satellite (SPS) system, which would ring the Earth in geosynchronous orbit with 5- by 20-kilometer solar-powered satellites designed to microwave the energy to the Earth. Another proposal for supplying power from space to the Earth

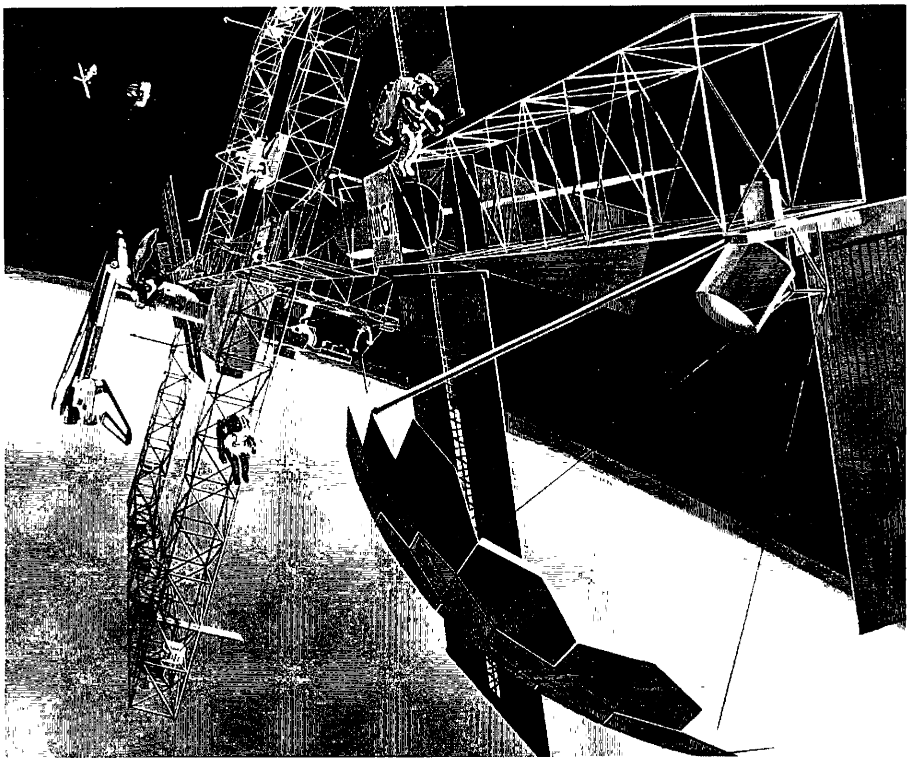


Figure 8

Solar Dynamic Power for the Space Station

In this artist's conception, a solar dynamic power generation system uses concentrated light from the Sun to heat a fluid, which turns a generator to provide electrical power for the space station. Solar dynamic power generation may have some advantages over solar photovoltaic: potentially higher efficiency per unit area of reflector and possibly lower cost for large power capacity. A solar dynamic system may also be easier to maintain.

uses large areas on the Moon for relatively low-efficiency photovoltaic devices utilizing indigenous lunar material, such as silicon. The lunar power station would also transmit energy to Earth by microwave.

The Sun's energy is a perpetual source of clean, nonpolluting power, and major technological advances in photoconversion and energy transmission could substantially alter any space scenario.

Low to Negligible Gravity

Many manufacturing processes may be enabled or improved by the utilization of the low to negligible gravity of space. An electrophoresis process for separating cells having small differential charges is being developed by private industry. In the absence of gravity, an electrical field can cause the desired cells to migrate toward a collector. The great selectivity of this process and the purity of its products may lead to drugs effective in the treatment of cancer, diabetes, and other diseases (see fig. 9). Other processes may produce new alloys, high strength glasses, and more efficient semiconductors. The more space transportation costs are reduced, the wider the range of economical microgravity processing will be. This is an area of potentially significant commercial investment.

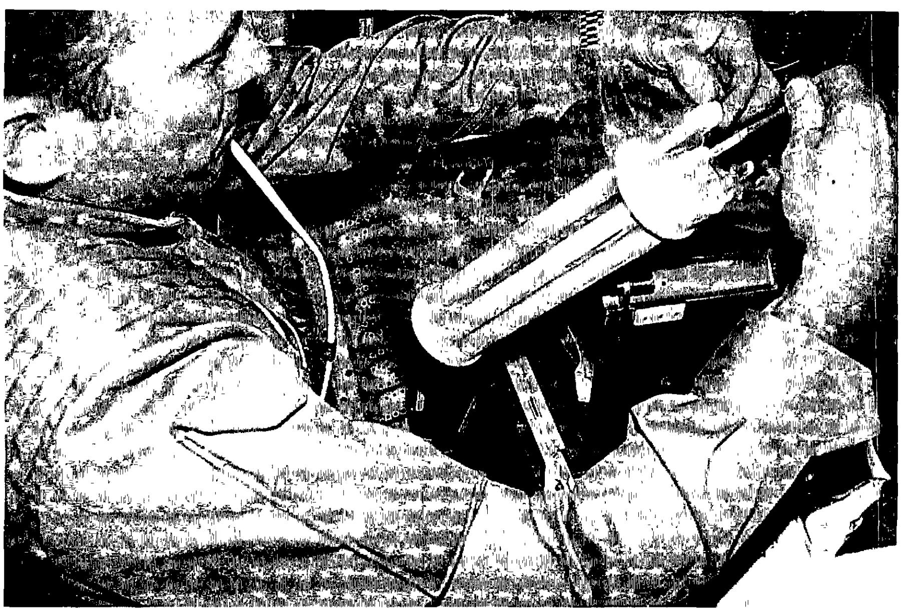


Figure 9

Electrophoresis in Space

Manufacturing or materials processing in the microgravity of space may prove to be a major activity. Here, astronaut Jack Lousma is handling an electrophoresis column used for human cell separation on the STS-3 flight. Space manufacturing and processing of biological and pharmaceutical materials may prove cost-effective because of the potentially very high value of these substances per unit mass.

Physical Location/View

Physical location in space and the view from off the Earth have shown themselves to be a resource of great benefit to the public (see figs. 10 and 11). The particular characteristics of the geosynchronous orbit, both from the standpoint of view (weather satellites) and from the standpoint of stability (communication satellites), have been heavily exploited and have provided substantial benefits in revenue and in public safety. Significant public and private (as well as joint venture) technology developments are under way to further utilize this unique space resource for communication, navigation, search and rescue, and other purposes. The location of astronomical facilities in space has been demonstrated to be of fundamental scientific importance (see fig. 12). Another potential utilization of location/view would be for recreation in low Earth orbit. Studies have shown that a market does exist for the public to use space as a recreational area, if transportation costs can be made affordable.

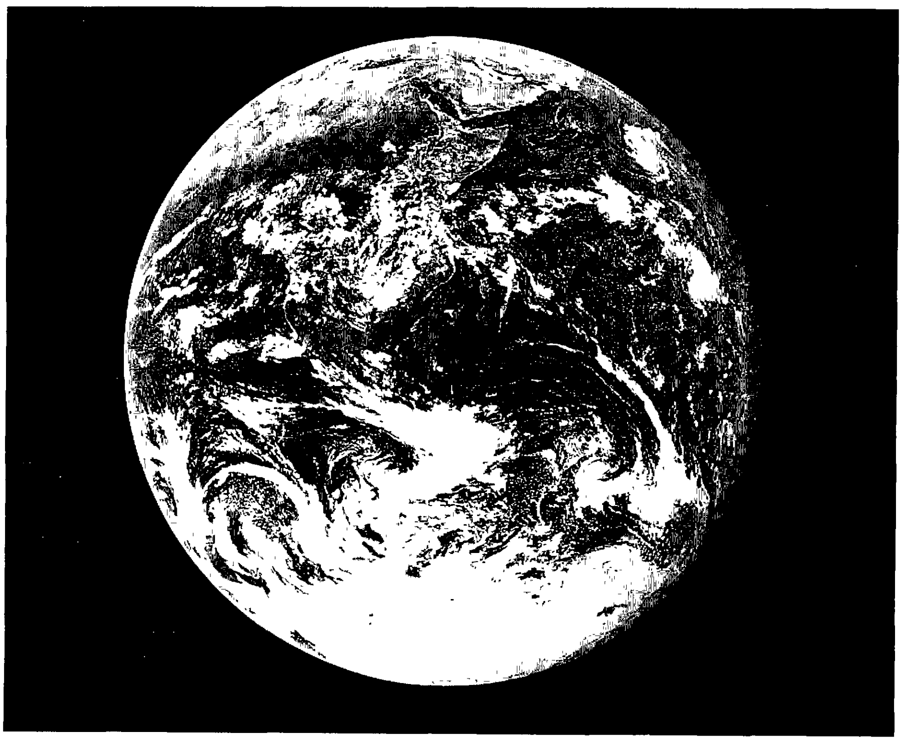


Figure 10

The "Big Blue Marble"

Location in space must be considered a resource in the sense that it enables some very valuable activities. In this whole Earth view taken by the crew of Apollo 17, it is apparent that large-scale weather patterns can be photographed, that the geology and vegetation of large land masses can be observed by remote sensing, and that many points on the Earth can be reached by a single data transponder for enhanced communication. Most of the economic payback from space activities has so far been in these three areas, all of which take advantage of location in space.

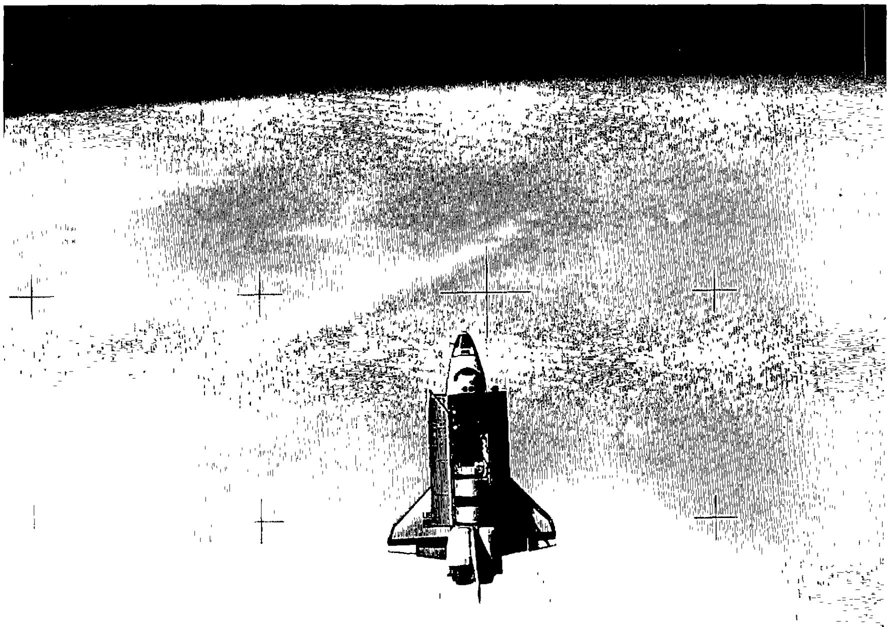


Figure 11

Space Shuttle and Horizon as Seen From the Shuttle Pallet Satellite (SPAS)

This is a satellite view of the Orbiter taken on the STS-7 mission The Orbiter had previously launched two communication satellites (Telesat Anik C2 and Palapa D), and the protective cradles for these satellites can still be seen in the cargo bay. The Space Shuttle has been used heavily as a launching vehicle for communication satellites. Much of this task may now be taken over by expendable launch vehicles. The location in space of communication satellites gives them such high value that the enormous expense of building and launching them can be paid back by revenues in a reasonable length of time.

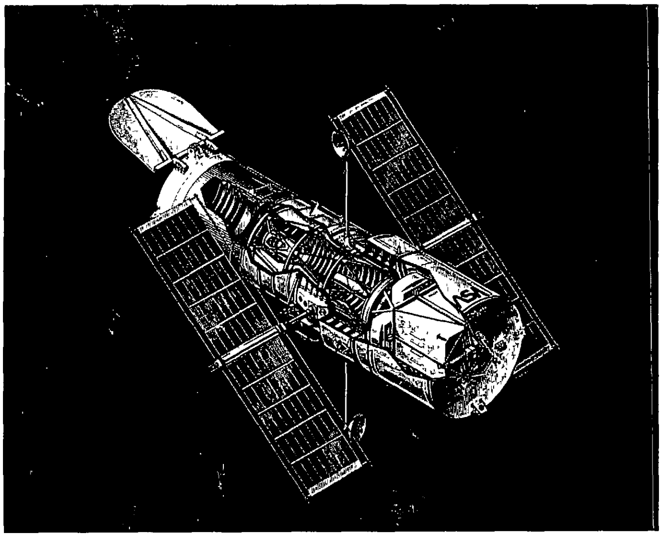


Figure 12

The Hubble Space Telescope

Another priceless advantage of a location in space is illustrated by this artist's concept of the Hubble Space Telescope. This telescope will be above the Earth's atmosphere, which greatly interferes with the optical clarity of an Earth-based telescope and which also absorbs important parts of the light spectrum. The Hubble telescope can be serviced in space and can even be returned to Earth by a Space Shuttle mission for extensive maintenance or overhaul, if needed. Eventually, telescopes on the Moon may also be feasible and desirable. Radio telescopes located on the far side of the Moon will avoid the ever-increasing electromagnetic noise from the Earth.

Other potential developments in the cultural and societal arena are certain to appear but difficult to quantify. Historical evidence suggests that humankind always modifies its culture and societal norms to adapt to major alterations of its sphere of influence. It is conceivable that artistic and sporting activities could find a role in space and may be marketable.

By way of concluding this section on space resources, we, the members of the workshop, want to stress that the list of space resources is not limited to those we have mentioned. Other usable resources might be isolation (for nuclear waste disposal or very hazardous research projects) and extreme temperature gradients (for heat engines).

Generic Scenarios for Utilization of Nonterrestrial Resources

In order to suitably characterize the future utilization of nonterrestrial resources, we should assess scenarios broad enough to bring to the surface all or most of the key technology issues. The exploitation of nonterrestrial resources encompasses a very broad range of potential products, benefits, resources, supporting systems, and technology requirements. The evolution of space activities into the 21st century also holds the potential for a much changed mix of space users, with increased levels of commercial, international, and military space activities. The objective of this section of the report is to view the broad range of mission alternatives that may use space resources and to select a few examples that illustrate a mix of mission characteristics.

Mission Characteristics and Options

Table 1 illustrates the variety of options that are possible for future missions. Most missions can be described by one or more of the options related to each item. Therefore, a specific mission can be characterized by a total set of option choices.

Mission goals: Four broad goal options are shown. The identification of relevant goals is imperative to advocacy of the overall program and its technology requirements. Each of the goals represents a valid component of the total space program. Although some goal from the leadership/human spirit class may be the only goal of a specific mission, most space missions have been dominated by a strong set of scientific or applications goals. Such human goals can often be attained with only marginal costs when added to more concrete goals.

TABLE 1. *Options for Aspects of Mission Development*

Item	Options *			
1. Goals:	Leadership Exploration Human spirit	Public applications	Commercial	Security Military
2. Participants: Type: Countries:	 Government National	 Government/commercial International	 Commercial	
3. Purpose:	Science/research	Enhanced mission	Valuable product	Prestige/power
4. Space resource:	Materials	Vacuum Energy	Gravity	Location/view
5. Resource location:	LEO GEO	LEO/cislunar (debris/expendables)	Lunar Asteroidal	Planetary (Mars & moons)
6. Product:	Materials Volatiles Low value solids High value solids	Information/data	Energy	Pleasure
7. Processing: Location: Type:	 In situ None	 LEO Automated	 Other Manned	
8. Transportation: Resource site / Processing site / Use site Mode:	 Same Chemical rocket	 In situ processing/ used elsewhere Aerobrake	 Intermediate site Other	 At use site
9. Infrastructure:	Earth-to-orbit transportation Orbital transfer vehicles	LEO space station	Observation instruments	Planetary bases or outposts

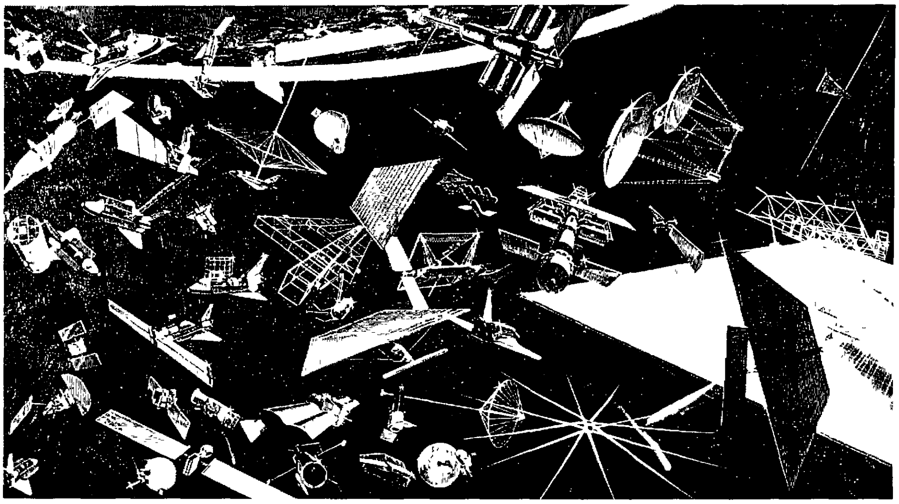
*The columns in this table do not represent related categories but are used simply to enumerate options for each item.

Participants: The mix of participants in space activities is rapidly changing from the historical dominance of the U.S.A.'s civilian space agency and the more military space effort of the U.S.S.R. In the United States, military funding of space activities now exceeds that of NASA. The U.S. program is encouraging commercial participation. And most of the advanced countries and many developing countries are pursuing space capabilities to increase their military options, to advance technology, and to gain prestige. These developments may drastically change the way in which space activities are pursued in the 21st century. It will be necessary for the nations of the world to agree on policies for the utilization of space resources because they are limited. Already at issue are the filling of geosynchronous Earth orbit and the problem of orbital debris.

Purpose: Use of space resources spans a range of purposes from pure science (planetary observations) through mission enhancement (such as in situ propellant production) to the production of products with value to a third party. National prestige and the development of new technology have been strong motivators of national space programs.

Space resource: The details of indigenous space resources have been discussed earlier in this section. We consider materials placed in space for one purpose and then recycled for another to be a special category of space resources.

Resource location: The location of the resource has tremendous implications for the transportation requirements of the mission and for the possibility of human participation. One early exploitation of space material resources may be the scavenging of Space Shuttle cryogenic propellants and external tank materials, which are potentially available in low Earth orbit. The development of resources on planetary bodies (Moon, Mars) is



Overcrowding in Space

This artist's concept shows a wide variety of existing and future satellites. In view are satellites for surveying Earth resources and mapping them, communication satellites, orbiting platforms, various types of space stations, solar power satellites, astronomical observatories, and manufacturing facilities. Geosynchronous orbit is already becoming crowded and satellite densities in other orbits must also be considered. This view also hints at the potential hazards of having large numbers of satellites in space; namely, the possibilities for collision and generation of orbital debris. The issue of orbital debris must be more carefully considered as space becomes more crowded.

Courtesy of Grumman Aerospace Corp.

considered essential to any long-term activities there.

Product: Products of value include not only materials but also energy, information (as with communication satellites), and possibly pleasure and entertainment (as represented by tourism and national parks).

Processing: The process for converting a raw resource into a valuable product, the location for this process, and whether or not humans are directly involved in the process are key considerations.

Transportation: Transportation between key locations, which include the operations base, the resource site, the processing site, and the use site, is one of the major factors in feasibility and achieving favorable economics. The transportation strategy, the transportation system, and the transportation technology level are key issues in this set of tradeoffs.

Infrastructure: The activities of each chosen mission will require that a set of facilities be established in space. These facilities will be a subset of this general set: (1) some form of transportation from Earth to orbit, (2) a service and operations station in low Earth orbit, (3) observation instruments, (4) a means of getting from LEO to higher orbits (orbital transfer vehicles), (5) bases or outposts, manned or otherwise, on various planetary bodies.

Selected Mission Examples

Four mission examples are shown to illustrate the variety of options in the various areas listed in the previous subsection. These four missions are not intended to be all encompassing; readers are encouraged to use table 1 to create and characterize other missions of interest.

Mission 1 – lunar or asteroidal propellant extraction: Table 2 and figures 13 and 14 illustrate the characterization of these missions, which were combined because of the high degree of similarity. Such a mission has many attractive features. It has a combination of goals, including elements of both exploration and commercialization, with a probable evolution from exploration to commercialization. Participants could combine government and private investment. The product could be used to enhance the basic mission in the early phases and provide a valuable output in the later phases of the program.

Development of the processing systems and transportation systems are key technology challenges. The infrastructure supports growth to exploitation of solid materials and can complement military technology requirements.

TABLE 2. *Lunar or Asteroidal Propellant Extraction*

	Item	Options				
1.	Goals:	Exploration	Public applications	Commercial		
2.	Participants:					
	Type:	Government	Government/commercial	Commercial		
	Countries:	National	International			
3.	Purpose:	Science/research	Enhanced mission	Valuable product		
4.	Space resource:	Materials				
5.	Resource location:			Lunar	Asteroidal	Moons of Mars
6.	Product:	Materials Volatiles				
7.	Processing:					
	Location:	In situ	LEO	Other		
	Type:	None	Automated	Manned		
8.	Transportation:					
	Resource site Processing site Use site	Same	In situ processing/ used elsewhere	Intermediate site		At use site
	Mode.	Chemical rocket	Aerobrake	Other		
9.	Infrastructure:	Earth-to-orbit transportation Orbital transfer vehicles	LEO space station	Observation instruments in LEO & GEO		Lunar base Asteroid outpost Mars base Phobos outpost

Mission 2 – climate modification for agricultural productivity: Table 3 illustrates this mission, which focuses on critical world population needs for food. This program would be a cooperative international government project and would exploit the energy resources of space. Options exist for utilizing nonterrestrial materials to construct space energy facilities. Requirements for transportation to GEO would be increased under this plan. The potential for direct benefits to major portions of the world's population could motivate a large-scale effort of this type.

Mission 3 – information or entertainment: Table 4 and figure 15 illustrate this mission area, which focuses on the development of commercial opportunities in space that affect the individual person. This effect is illustrated in two ways: (1) bringing world information and communication to the individual (i.e., complexity inversion) and

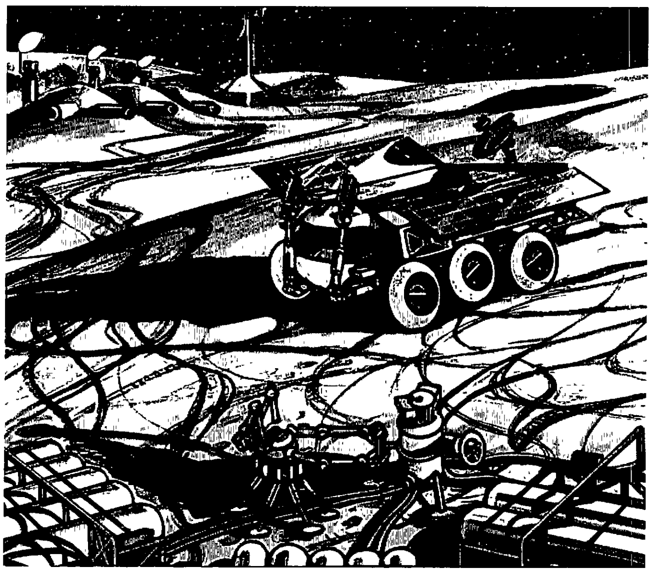


Figure 13

A Propellant Tank Farm on the Lunar Surface

Here, robots are moving tanks of liquid oxygen into position for transport into space. Liquid oxygen is produced in the reactor units shown in the background. These reactors are heated by solar radiation, which is reflected into them by Sun-tracking mirrors. Other possible export products include hydrogen, bulk materials for shielding, and metals for space construction.

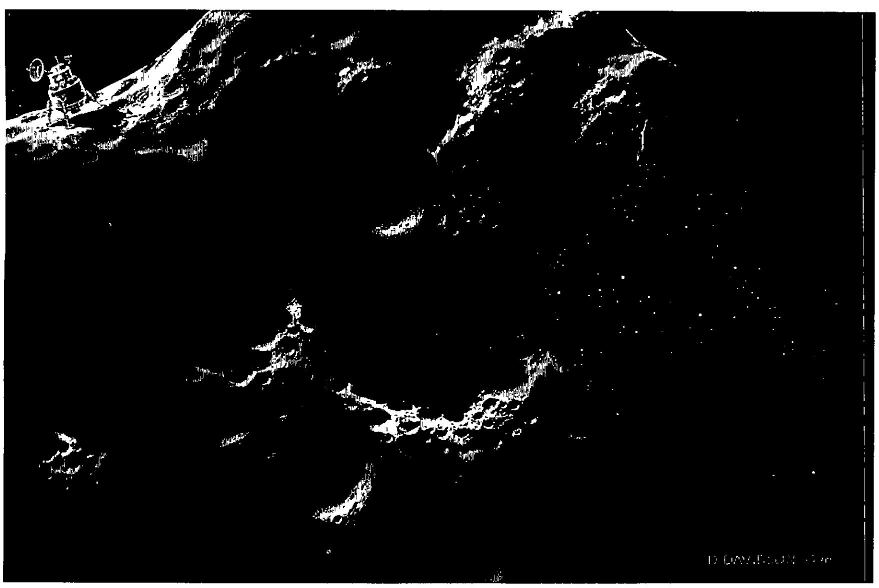


Figure 14

Asteroid Mining

Asteroids also have resource potential, notably the potential for providing water, which can be decomposed into hydrogen and oxygen for propellant use. Asteroids may have rough cratered surfaces, as illustrated in this painting. If they are water-rich, they are likely to be similar to carbonaceous chondritic meteorites, which are very black, with extremely low albedos. Such asteroids may be rather soft and friable and thus easily mined.

Artist: Dennis Davidson

TABLE 3. *Climate Modification for Agricultural Productivity*

Item	Options			
1. Goals:	Human spirit	Public applications		
2. Participants:				
Type:	Government			
Countries:		International		
3. Purpose:			Valuable product	
4. Space resource:		Energy		
5. Resource location:	GEO		Lunar	
6. Product:			Energy	
7. Processing:				
Location:	In situ	LEO	Other	
Type:	None	Automated	Manned	
8. Transportation:				
Resource site / Processing site / Use site	Same	In situ processing/ used elsewhere	Intermediate site	At use site
Mode:	Chemical rocket	Aerobrake	Other	
9. Infrastructure:	Earth-to-orbit transportation Orbital transfer vehicles	LEO space station	Observation instruments in LEO & GEO	Lunar base

(2) enabling tourist-type access to space. If the much lower transportation costs necessary to enable tourism could be achieved, then the expansion of the market to the individual would enable tremendous business and economic opportunities.

Mission 4 – Strategic Defense Initiative (SDI): Table 5 illustrates a mission to support the strategic defense initiative. SDI systems could benefit from large amounts of low-grade shielding materials for systems in low Earth orbit. Although there are some areas of technology commonality with mission 1, the goals, participants, and products of interest are substantially different from those of the other missions. Also, critical tradeoffs would be decided on the basis of much different assessment criteria.

TABLE 4. *Information or Entertainment*

Item	*Options*			
1. Goals:			Commercial	
2. Participants:				
Type:			Commercial	
Countries:	National	International		
3. Purpose:			Valuable product	
4. Space resource:				Location/view
5. Resource location:	LEO GEO		Lunar	
6. Product:		Information		Pleasure
7. Processing:				
Location:				
Type:	None			
8. Transportation:				
Resource site / Processing site / Use site	Same			
Mode:	Chemical rocket	Aerobrake	Other	
9. Infrastructure:	Earth-to-orbit transportation Orbital transfer vehicles	LEO space station	Observation instruments in LEO & GEO	Lunar base

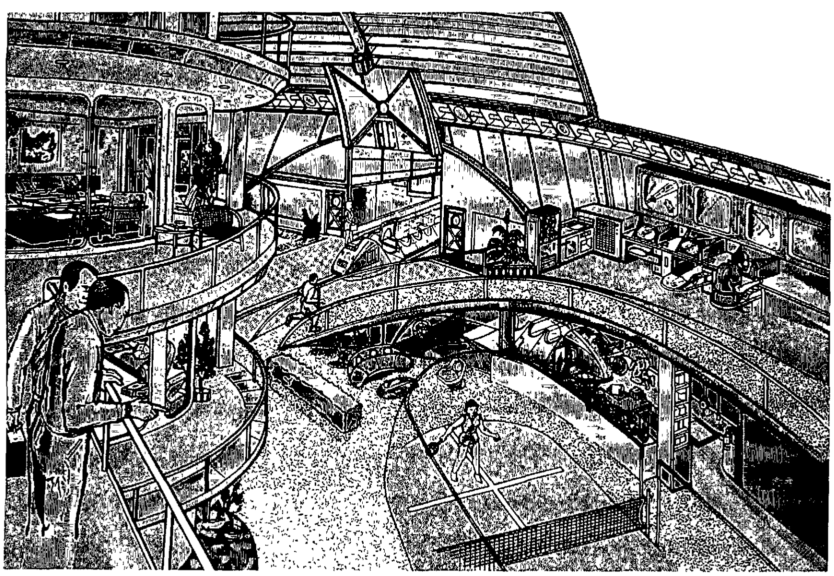


Figure 15

Tourism

Tourism may eventually be an important activity in space or even on the Moon. This drawing shows a hotel module at a lunar base. The hotel has recreation facilities, viewing ports, and TV monitors for viewing activities at remote locations. Excursions onto the lunar surface are made on the small monorail train. While tourism will not be possible very early in the development of a lunar base, it might be a logical intermediate step between a utilitarian base and a self-supporting lunar colony.

TABLE 5. *Strategic Defense Initiative (SDI)*

Item	Options			
1. Goals:				Security Military
2. Participants: Type: Countries:	 Government National			
3. Purpose:				Prestige/power
4. Space resource:	Materials			Location/view
5. Resource location:	LEO GEO	LEO/cislunar	Lunar Asteroidal	
6. Product:	Materials Low value solids	Information/data	Energy	
7. Processing: Location: Type:	 In situ None	 LEO Automated	 Other Manned	
8. Transportation: Resource site Processing site Use site	Same	In situ processing/ used elsewhere	Intermediate site	At use site
Mode:	Chemical rocket	Aerobrake	Other	
9. Infrastructure:	Earth-to-orbit transportation Orbital transfer vehicles	LEO space station	Observation instruments in LEO & GEO	Lunar base Asteroid outpost Phobos outpost

Summary: Space Resource Mission Alternatives

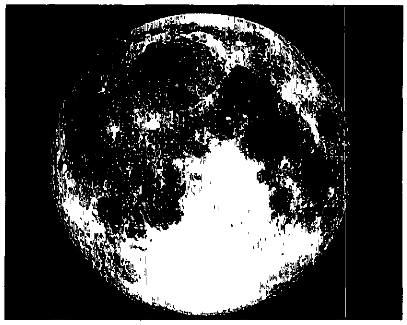
The mission options of table 1 present the basis for the assessment of a broad range of space resource scenarios. The four example missions were selected to illustrate the variety of possible options. Issues, systems, and technologies with common threads in these missions should be of particular interest to long-range planners.

To clarify the technology issues associated with this broad range of possible goals, we developed in greater detail two variants of the first goal, lunar or asteroidal propellant extraction. We chose to develop these two scenarios because they are driven by the utilization of space resources rather than merely augmented by the availability of such resources. Because of the focus of these scenarios, we expected their technological requirements to be clearer.

The first alternate scenario (fig. 16) emphasizes lunar and asteroidal resource extraction, with manned Mars missions as a long-term objective. The second alternate scenario (fig. 17) follows a broader developmental strategy that places less emphasis on lunar and asteroidal propellants and more emphasis on exploration and scientific study of the solar system.

The Moon

The Moon has a wide variety of terrains, rock types, and regolith types. While much has been learned from analysis of the American Apollo samples and of the Soviet Luna samples, most of the Moon has neither been sampled nor been mapped by orbital chemistry mappers. Consequently, the potentially useful resources are not well understood; additional exploration may bring some surprises.



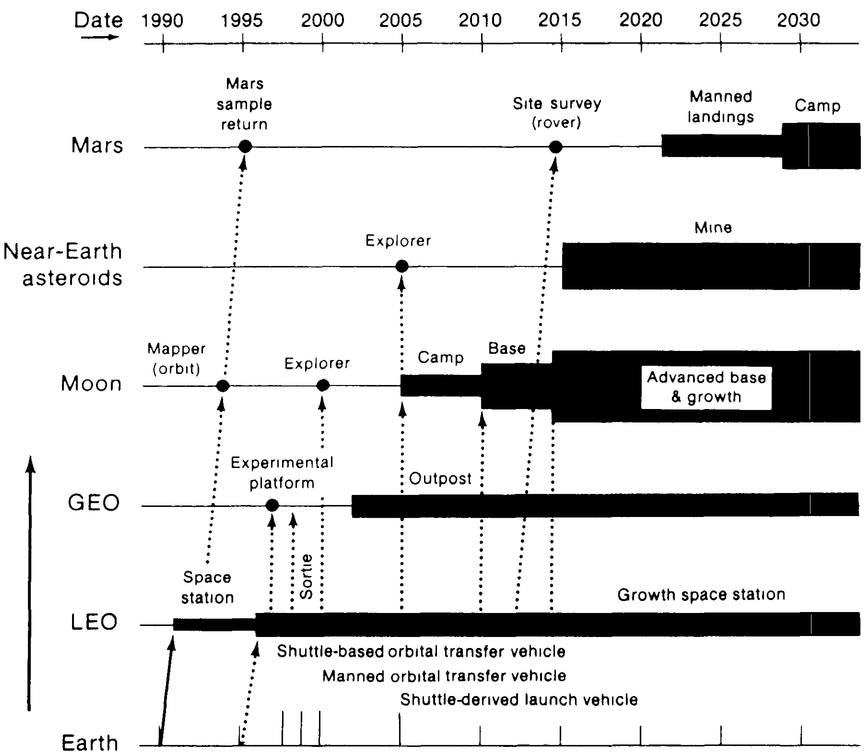


Figure 16

Scenario for Space Resource Utilization

Space resource utilization, a feature lacking in the baseline plan, is emphasized in this plan for space activities in the same 1990-2035 timeframe. As in the baseline scenario, a space station in low Earth orbit (LEO) is established in the early 1990s This space station plays a major role in staging advanced missions to the Moon, beginning about 2005, and in exploring near-Earth asteroids, beginning about the same time. These exploration activities lead to the establishment of a lunar camp and base which produce oxygen and possibly hydrogen for rocket propellant. Automated missions to near-Earth asteroids begin mining these bodies by about 2015, producing water and metals which are returned to geosynchronous Earth orbit (GEO), LEO, lunar orbit, and the lunar surface. Oxygen, hydrogen, and metals derived from the Moon and the near-Earth asteroids are then used to fuel space operations in Earth-Moon space and to build additional space platforms and stations and lunar base facilities. These space resources are also used as fuel and materials for manned Mars missions beginning in 2021. This scenario might initially cost more than the baseline scenario because it takes large investments to put together the facilities necessary to extract and refine space resources. However, this plan has the potential to significantly lower the cost of space operations in the long run by providing from space much of the mass needed for space operations.

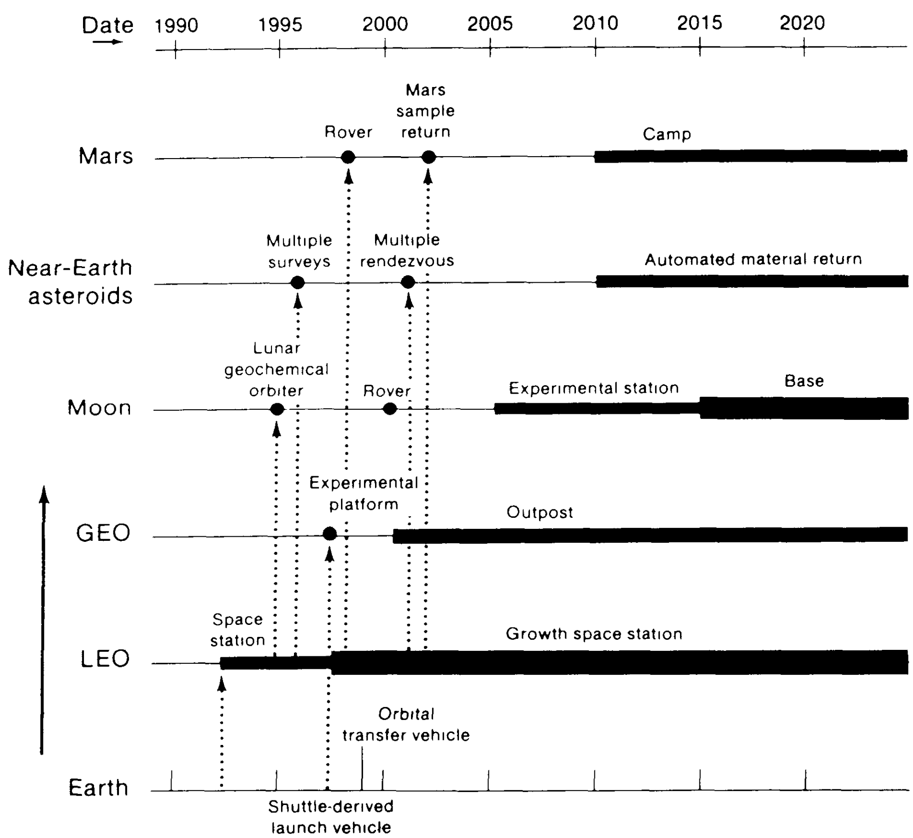
Phobos

The resource potential of asteroids and the satellites of Mars (Phobos shown here) is even less well understood than that of the Moon. It may be that many asteroids as well as the satellites of Mars have abundant useful resources, including water and hydrocarbons. Additional exploration is clearly needed before the resource potential of these objects can be evaluated.

Figure 17

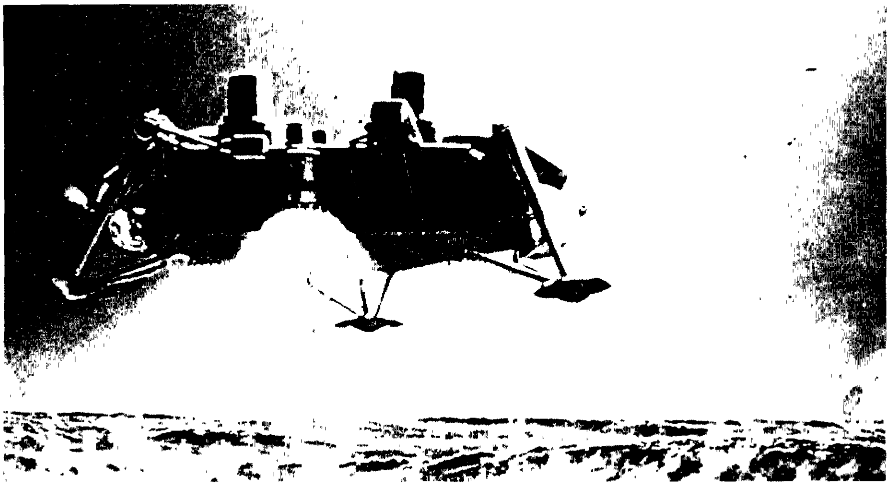
Scenario for Balanced Infrastructure Buildup

In this scenario, each location in space receives attention in a balanced approach and none is emphasized to the exclusion of others. The scenario begins with the establishment of the initial space station about 1992. This is followed by the establishment of a manned outpost in geosynchronous Earth orbit (GEO) in 2001, an experimental station on the Moon in 2006, and a manned Mars camp in 2010. In parallel with these manned activities, many automated missions are flown, including a lunar geochemical orbiter and a lunar rover, multiple surveys of near-Earth asteroids and rendezvous with them, and a martian rover and a Mars sample return. Automated mining of near-Earth asteroids beginning in 2010 is also part of this scenario.



Mars Lander

Here an unmanned lander is descending to the martian surface. A variety of unmanned scientific missions have been proposed for Mars, including the most ambitious and potentially most useful: sample collection and return. Such missions would be useful precursors to piloted Mars expeditions, but they may not be absolutely necessary before people go to Mars.



Impacts of Sociopolitical Conditions

Ben R. Finney

To what extent will scenarios of space development, and the choice of technologies to carry these out, hinge upon future social, economic, and political factors outside the range of currently discussed scientific and commercial rationales for venturing into space? Outside factors have greatly influenced the course of space development in the past–as witness the initial drive to develop large rockets and the subsequent race for the Moon. Although space technology has now reached a level where it has demonstrable scientific and commercial utility, there is no reason to assume that this utility must exclusively or even largely determine the course of space development.

We should be prepared to consider how changing conditions, outside of space development per se, may impact that development. For example, an emphasis on space weaponry, and defense against that weaponry, might lead to a significant requirement for lunar or asteroidal materials for shielding. Alternatively, superpower rivalry might once again be expressed in peaceful competition in space, where the goal of setting up the first Moon or Mars base could override the logic of orderly, evolutionary development. Or a global environmental crisis might stimulate an effort to magnify remote sensing capabilities and lead to the revival of the solar power satellite concept. Geopolitical developments might lead to major international cooperation in space–such as between the United States, Europe, and Japan or between the capitalist and socialist blocs or between First World and Third World nations or some combination of these. Finally, a major cultural upheaval–such as might be occasioned by the discovery, through NASA's Search for Extraterrestrial Intelligence (SETI) program, of intelligence in some other star system–could dramatically impact our conception of the human role in space.

It is, of course, impossible to predict the future. However, any scenario of space development, and the technology requirements engendered, in effect assumes a future vision–not only of that development but also of outside forces and events. Space development scenarios are inherently part of larger scenarios of human development.

Common Technologies

Terry Triffet

Common to the baseline and alternative scenarios presented above are a number of intersecting or nodal technologies. That is, regardless of whatever divergent paths such developments may take, they will intersect at these points and cannot move beyond them until certain problems specific to these technologies have been solved. Thus, in a sense, these nodes are the invariants of the system, and concentrating attention on them should be the most efficient way to proceed. It is a primary purpose of this study to point to these pivotal technologies and highlight their barrier difficulties.

Transportation

Surely the most fundamental nodal technology, because of its high leverage on the entire evolution of space development, is transportation. The cost of delivery into low Earth orbit, which had been moving downward as a result of Space Shuttle efficiency, is now, as a result of the *Challenger* accident, estimated to be over $3000 per pound and the extrapolated cost for delivery to the Moon over $20 000 per pound.

Technologies that have been proposed to cut delivery costs to low Earth orbit and beyond fall into three categories: (1) improvements to the performance of earthlift vehicles, (2) development of space-based orbital transfer vehicles and associated propulsion technologies, and (3) production of propellants using nonterrestrial resources.

Complex system tradeoffs are required to determine which approach will be optimal in a given scenario. For example, reducing the cost of Earth-to-orbit (ETO) transportation will reduce by a similar proportion the cost of Earth-to-Moon transportation and will thus reduce the cost of obtaining propellants from the Moon. However, if the ETO costs are reduced enough, the expense of establishing a lunar facility to produce propellant to reduce transportation costs may not be merited. Aspects other than transportation costs may need to be considered. For example, at some level of activity, modification of the Earth's environment due to high launch rates may become intolerable.

The first objective in all scenarios is to reduce the cost of ETO options. The general approach is well understood, and several options are discussed later in this report. Expected costs for various options are given in table 6. Shuttle-derived launch vehicles are a class of vehicles in which the manned elements of the Space Shuttle are replaced by cargo-carrying capacity (see fig. 18). Heavy lift vehicles apply Space Shuttle propulsion

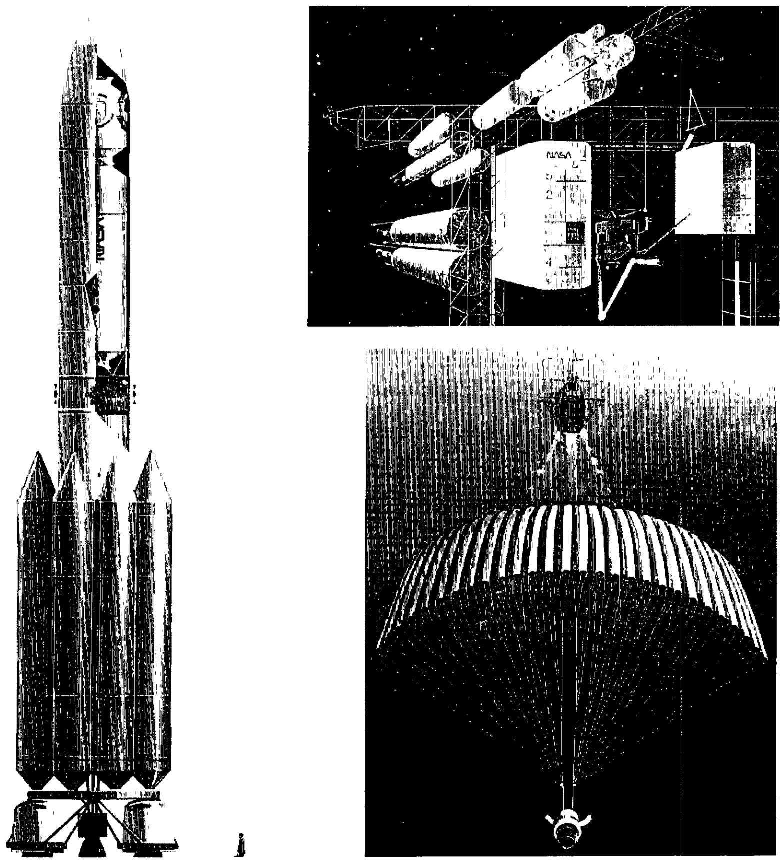


Figure 18

Consort

Since the Challenger *accident, it has become increasingly clear that unmanned launch vehicles must be developed to transport large cargoes into space at relatively low costs. In the concept shown here, the liquid-fueled* Consort *vehicle is launched into space with five Space Shuttle main engines. At the staging point in the ascent, four of these engines are jettisoned, returned to Earth by remote-controlled parachutes, recovered dry by a ship with arresting gear, and reused. The eight strap-on oxygen and hydrogen tanks are also jettisoned and allowed to fall into the ocean. The second stage delivers its cargo housed in a Titan IV fairing. This second stage, which includes one Space Shuttle main engine, internal fuel tanks, and support equipment, might then become the basis of an orbital transfer vehicle.*

Courtesy of Davis Aerospace Company

TABLE 6. *Potential Earthlift Options*

1. Space Shuttle	$3300/lb
2. Shuttle-derived launch vehicle	$500-1000/lb
3. Heavy lift vehicle	$300-500/lb
4. Hybrid electromagnetic launches and rockets	< $300/lb

Figure 19

"Fat Albert"

Another approach to the launch of heavy cargoes is a massive single-stage-to-orbit booster, such as "Fat Albert," from a 1976 design study. This booster has 48 engines, half of which burn liquid hydrogen and half of which burn rocket propellant type 1 (RP-1). After putting its cargo into low Earth orbit, the booster makes a deorbit burn, reenters the atmosphere, and then uses some of its engines to decelerate to near-zero velocity before touchdown in water, where it is recovered. Tradeoffs between boosters that are completely reusable and boosters that are totally expendable include complexity, design and manufacture costs, operation costs, and recovery and refurbishment costs. It is not always obvious which concept will ultimately be more cost-effective.

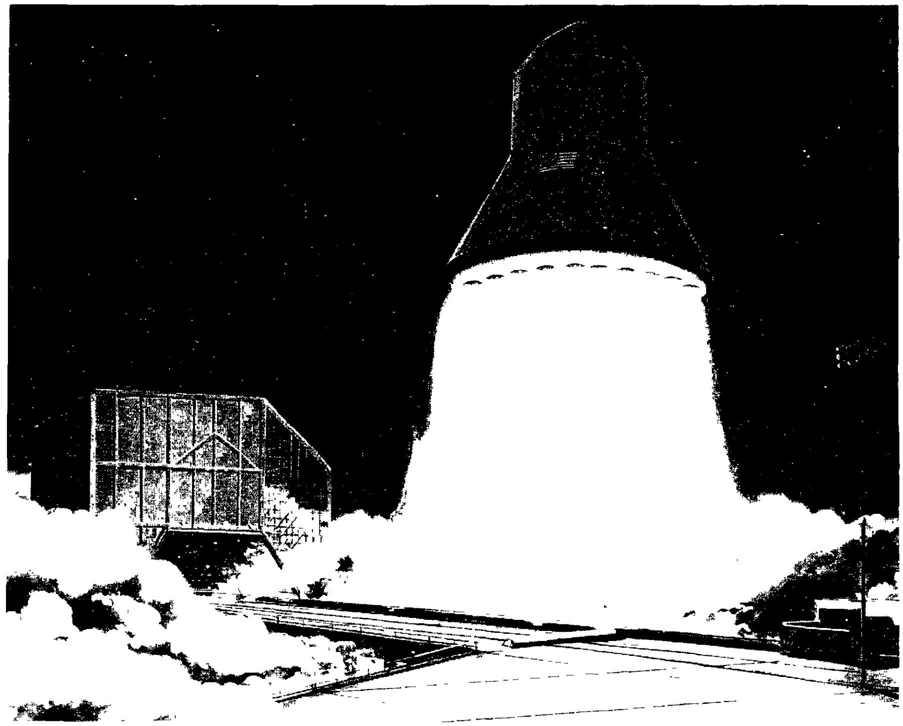


Figure 20

Lunar Orbit Space Station

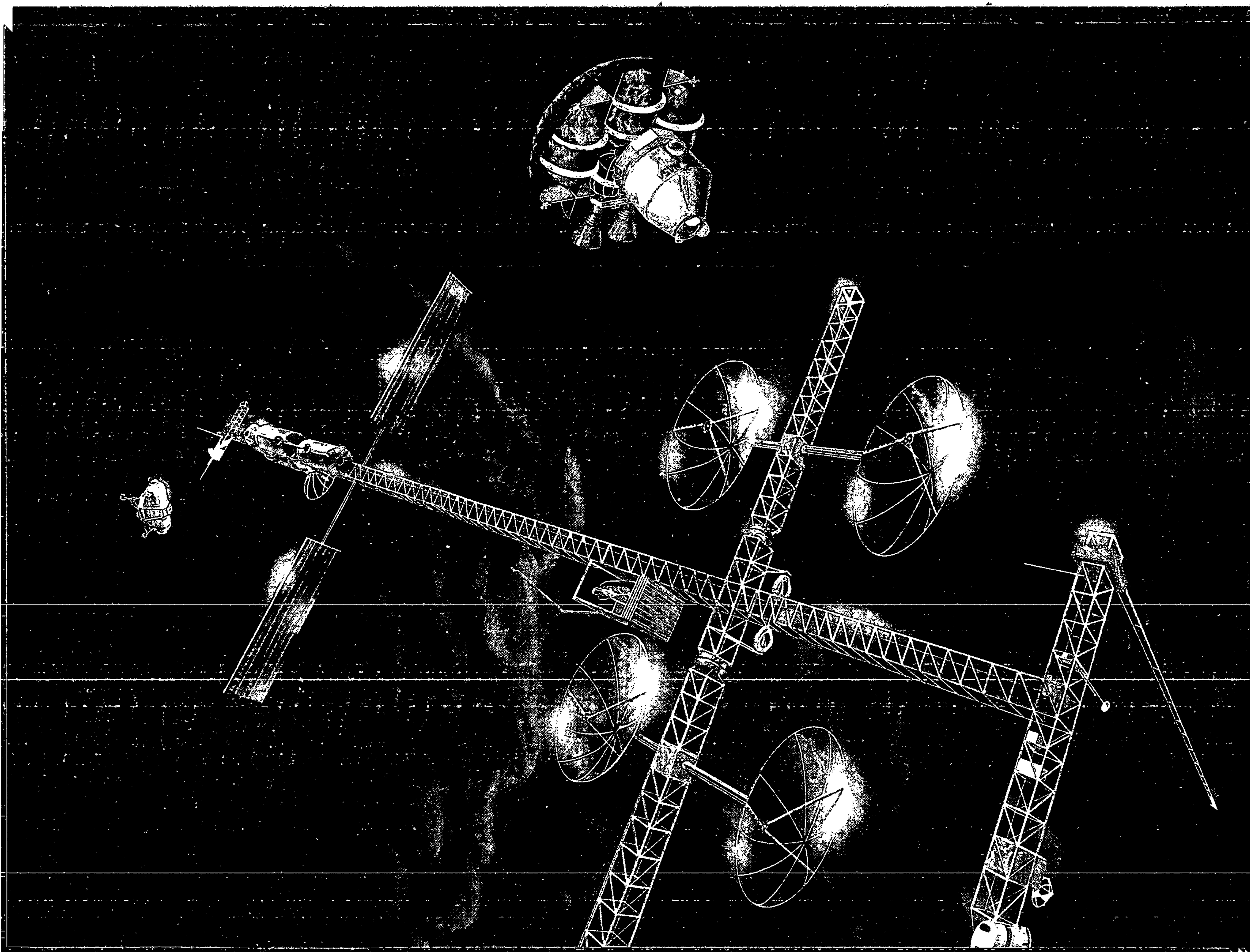
Proximity to lunar-derived propellant and materials would make a space station in orbit around the Moon an important transportation node. It could serve as a turnaround station for lunar landing vehicles which could ferry up liquid oxygen and other materials from the lunar surface. An orbital transfer vehicle could then take the containers of liquid oxygen (and possibly lunar hydrogen) to geosynchronous or low Earth orbit for use in many kinds of space activities. A lunar orbit space station might also serve as a staging point for major expeditions to other parts of the solar system, including Mars.

Artist: Michael Carroll

technology to a new class of large rockets (see fig. 19). Hybrid systems, air-breathing rockets, and electromagnetic propulsion technologies have also been studied.

Development and improvement of the performance of space-based orbital transfer vehicles involves propulsion technology, aerobraking technology, and lightweight structures. Aerobraking is a technology that replaces the propulsion system for deceleration upon return to Earth with an aerodynamic deceleration device. The task is to build an aerodynamic braking system that is lighter than the propulsive braking system. Lightweight structures improve performance by exchanging vehicle weight for payload weight. The payoff is almost always greater than 1 pound of payload for each pound of structure, because structure must be carried throughout all the vehicle's velocity changes whereas the payload is usually dropped off somewhere along the way.

Propulsion technology for orbit-to-orbit transportation involves a wider variety of options because low-thrust systems are usable and the spacecraft do not have to travel through a planetary



atmosphere. The list of options in table 7 is most likely incomplete.

Using propellant produced in space for orbital transfer and lift-off from planetary surfaces is of interest because the energy required to achieve low Earth orbit from either asteroids or a lunar base is much lower than that required to fight the gravity well of Earth. (See figure 20.) For a system to be viable, the cost of developing and operating the nonterrestrial facility must be less than the cost of delivering propellant from Earth. Thus, in general, the larger or more remote from Earth the usage, the more competitive the nonterrestrial resource will be.

Before costs can be assigned to the products, extensive development of process concepts and operational techniques is required. However, table 8 lists potential sources and types of propellants, which will be the focus for technology development.

TABLE 7. *Propulsion Technology Options for Orbital Transfer Vehicles*

1. Chemical – high performance O_2/H_2
2. Thermal – nuclear, solar, laser
3. Electric – ion accelerators, mass accelerators
4. Light – solar sails
5. Tethers – momentum storage and exchange, plasma dynamic thrusting and power production

TABLE 8. *Nonterrestrial Propellant Options*

1. Asteroids – water for liquid O_2 and liquid H_2
2. Moon – oxygen-hydrogen (Earth-supplied hydrogen), oxygen-silane (Earth hydrogen for silane), oxygen-aluminum (Earth-supplied binder)
3. Shuttle external tanks in orbit – aluminum and lunar or Earth oxygen
4. Electric propulsion – solar energy and nonterrestrial mass (lunar oxygen), electromagnetic accelerators and solid reaction mass, nuclear thermal energy and nonterrestrial mass, hybrid electromagnetic launchers and rockets

Energy

Equal in importance to transportation as a nodal technology is the development of energy sources in space. Space operations are impossible without appropriate power supplies; and any projects involving extended human activities in this hostile environment will necessarily be energy-intensive. Energy technology can be divided into two general classes: energy sources transported from Earth (chemical, nuclear) and those using in situ resources. Both classes will be utilized in the development scenarios considered.

Solar energy is usable as far out as Mars (and possibly Jupiter, using high concentrator systems). Beyond Jupiter, solar energy is too diffuse to be gathered in useful amounts. From there out, other sources, such as chemical and nuclear, are required.

The photovoltaic system with electrochemical storage has been the mainstay of space power to this time and will remain a serious contender for future space applications. This passive system is relatively maintenance-free and thus offers low life-cycle costs. Advanced photovoltaic systems, such as radiation-resistant indium phosphide cells and high-efficiency point-contact cells, promise greatly improved performance. Their potential is further increased when they are coupled with storage systems with high energy densities, such as advanced regenerative fuel cells and innovative bipolar batteries.

Solar concentrators with dynamic systems (Stirling-, Brayton-, or Rankine-cycle thermal engines) offer an alternative to photovoltaic arrays. This technology becomes increasingly attractive as power demand goes up. The compactness of a solar thermal dynamic system is an advantage for missions subject to aerodynamic drag; its smaller cross section may significantly reduce the demand for orbit maintenance propellants. The ability of such a system to produce high point-source temperatures (several thousand versus one or two hundred degrees) make it a candidate for an integrated thermal electric distribution system; in such a system, the waste heat from the thermal engine could be piped in and used directly for onboard processes.

On the other hand, solar dynamic technology is less advanced than photovoltaic technology, and thus a greater development effort would be needed. Experience has been accumulated in solar Rankine systems, Brayton rotating machinery, and a Stirling free-piston engine. But problems remain in heat receiver design, materials compatibility, concentrator design, and heat rejection and thermal control systems. Nevertheless, because its power characteristics more closely resemble those of conventional sources, this alternative should be vigorously pursued.

Nuclear reactor energy sources deserve special mention (see fig. 21). Though posing formidable transport problems because of their mass, they offer high power levels, high temperatures, and long unattended operating times. In cases where solar energy is not continuously available (e.g., shadowed by Earth; on most of the lunar surface), a nuclear system may even have a mass advantage because a solar system would require an energy storage subsystem during shadowed periods. The shielding required to protect people from the radioactive energy source could, in planetary installations, be provided using local materials.

The technology underlying nuclear power is well understood, a large amount of Earth-operating experience has been accumulated, and miniaturization efforts are well advanced. Because this energy resource could take the greatest advantage of existing power technology, it, too, should be pursued with high priority. It could probably be ready for safe, reliable, and versatile use before any of the others.

Technologies for transmission and delivery of power in space also require development. Use at or near the point of collection in space or on the Moon offers minimal technologic challenge. Beamed transmission (laser, microwave) is considered applicable on the Moon or from place to place in space. Rectenna development is under way. Transmission from space to Earth faces additional problems but may also be a viable concept.

A variety of other technologies bear on our ability to collect, condition, store, and utilize energy in space. Conversion of solar or nuclear energy through chemical processing to produce propellants is one of these. The use of tethers to transfer momentum is another. Storage of energy for use in peak periods and for solar energy systems with intermittent illumination (like the lunar surface) is especially important. These technologies and others may have significant roles in a mature space operations system.

With the advent of high-temperature superconductivity (now in the range of liquid nitrogen), many additional advances in space power systems are on the horizon. An example is superconducting magnetic energy storage. Its advantages include high charge-discharge efficiency, less mass (because less refrigeration is required), and increased operating flexibility. If superconductor temperatures can be brought up to 0°C, the system, buried about 1 meter below the surface, could operate without any refrigeration through the lunar day/night cycle.

Other advances could improve future space power system applications. System control and monitoring by means of artificial intelligence could enhance autonomous power system operation. Advanced heat rejection systems such as the liquid droplet radiator could greatly reduce power system mass.

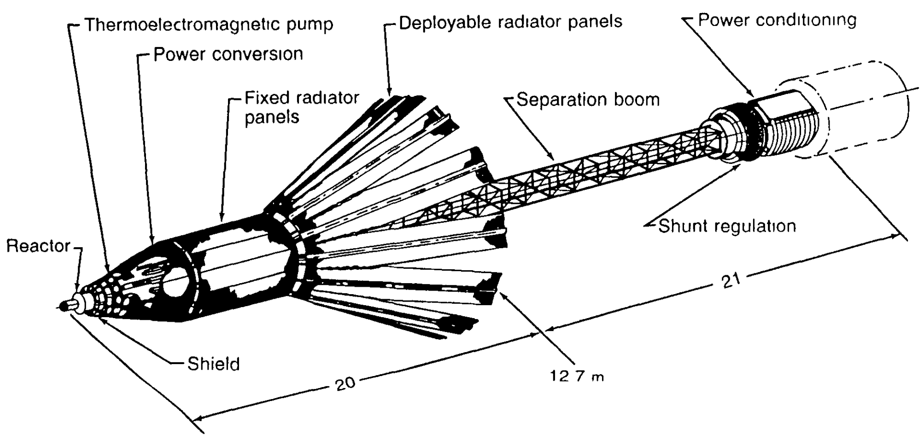


Figure 21

SP-100

The "SP-100" (not an acronym) is a nuclear power reactor for space applications It has a nominal design power of 100 kW and uses a closed-cycle working fluid heated by the small reactor, thermocouples both to convert thermal energy to electric power and to operate the pump moving the working fluid, and both fixed and deployable radiators to reject the waste heat. Most of the cone-shaped structure in the illustration is radiator surface. Nuclear reactors are currently used in space to power some Soviet intelligence satellites. And radioisotope generators have been used in space for many years, including use on the Apollo lunar surface experiments package (ALSEP) and the Voyager spacecraft.

Computing Technology

Computing technology, or more specifically the development of software for knowledge-based information and control systems, is a critical area. In the case of manned operations, greatly improved systems are needed to reduce the number of humans required, complement their capability, and relieve them of hazardous and routine tasks. The natural first step should be to expand the capabilities of the computing system already central to every operation in space. This step would involve further reducing processing time and increasing main memory, while adding a more versatile communications interface and continuing to reduce the system's weight and physical dimensions. Ideally, in addition to its data collection and "housekeeping" management functions, this machine should offer access to an extensive body of mission-specific information, and each person present should have an open channel to it at all times. Moreover, this system should be capable of self-contained operation, in case communications with Earth are interrupted.

To accomplish all these improvements is well within the range of contemporary computing technology. Also within that range is the possibility of incorporating appropriate expert system programs which may make rapid, error-free decisions and, if required, explain their reasoning. Together with instant access to a self-contained and specialized data base, this capability is essential to the success of even the simpler kinds of missions discussed above in the scenarios section. For the more complex missions, such as asteroid or lunar resource acquisition and processing, "intelligent" robotic assistance will be needed.

Given the present state of computing technology, it is entirely practical to target development of operational expert systems that incorporate strategic models and natural laws, weighted decision-making algorithms, and complex data frames, in addition to elementary inference engines, algorithms, and data bases of single facts. Such systems (see fig. 22) would possess the potential not only of assisting humans to make accurate, informed decisions under pressure but also of expanding the breadth and depth of human thought on this new frontier.

For extensive LEO, GEO, asteroidal, low lunar orbit, or lunar base operations, the economic advantages of using automated systems are plainly evident. These systems would be capable of supporting humans by making simple instant decisions, such as course- and handling-corrections based on sensor input, and of carrying out involved tasks under remote control. No life support system or protective environment would be needed, exposure to hazardous conditions would be no problem, and boredom, no factor. We must stress that the recommended technology objectives are to develop more intelligent robots, not to eliminate humans from operations in space. Both are needed. Robot or automated systems are envisioned to be synergistic with humans (see fig. 23). Structuring the objectives in this way would greatly improve the chances of creating these sophisticated automatic systems within the time available.

Materials Processing

Materials processing technology is required to transpose to the space environment familiar terrestrial processes, such as mining, ore concentration, extraction of useful materials, and manufacturing (see fig. 24). Even though the specific processes to be developed are mission-dependent, materials processing in general must be regarded as fundamental, because it changes the nature of the space enterprise from dependence on the Earth for all materials to the degree of independence afforded by the use of indigenous materials. Some

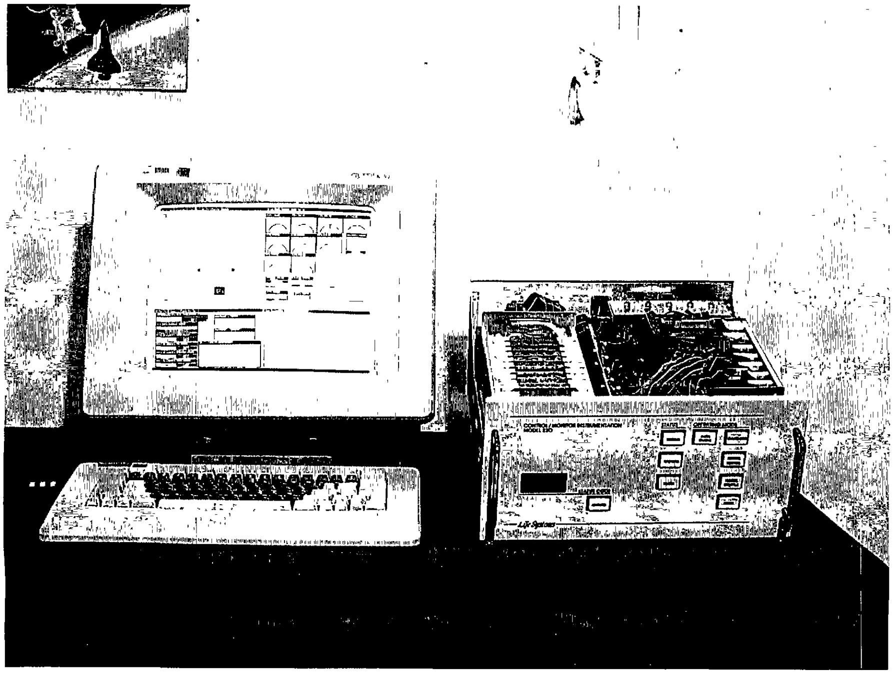


Figure 22

Expert System

"Expert system" is a term used to refer to an integrated computer and physical system in which very comprehensive software manages the system, handles a large variety of states and conditions, and even reacts to unexpected situations. Here is a prototype for an expert system that controls the removal of CO_2 from a space station habitation module. This system continuously monitors the CO_2 levels, gives instant readouts of environmental conditions from any terminal, provides feedback to reduce the levels as needed, and offers a variety of controls, checks, balances, and alarms on the condition of the environmental habitat atmosphere. As computer technology improves, such systems become more practical and less expensive.

Figure 23

Robot Rescuing an Astronaut on the Lunar Surface

Completely automated robots are a logical extension of comprehensive expert systems. Here, a robot with a contained expert system is rescuing a worker who has become ill while making a geological survey on the lunar surface Although such robots could also be teleoperated from a control room, a completely automated version with a self-contained expert system might be the eventual goal As the technology improves, teleoperated and expert system robots will become more and more useful for hazardous space activities, including lunar surface operations. Ultimately, many of the routine surface operations at a lunar base may be performed by such robots, leaving for humans the activities, such as scientific exploration, requiring very nonroutine observations and decisions.

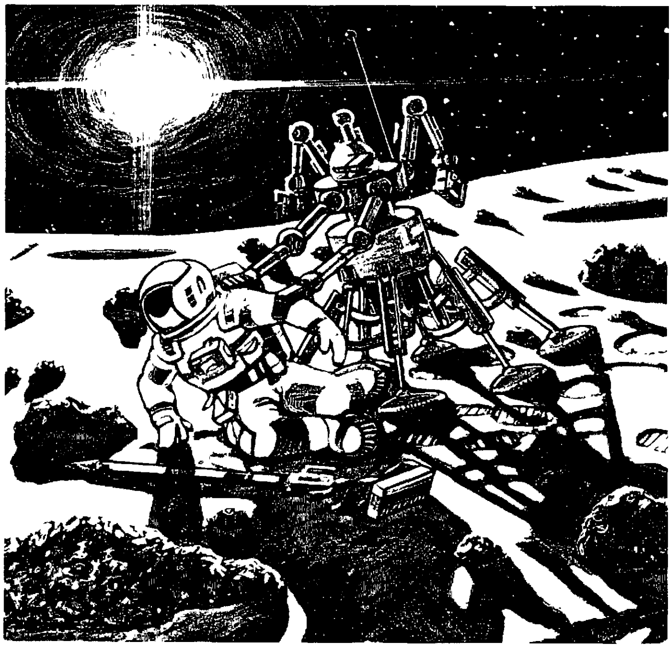
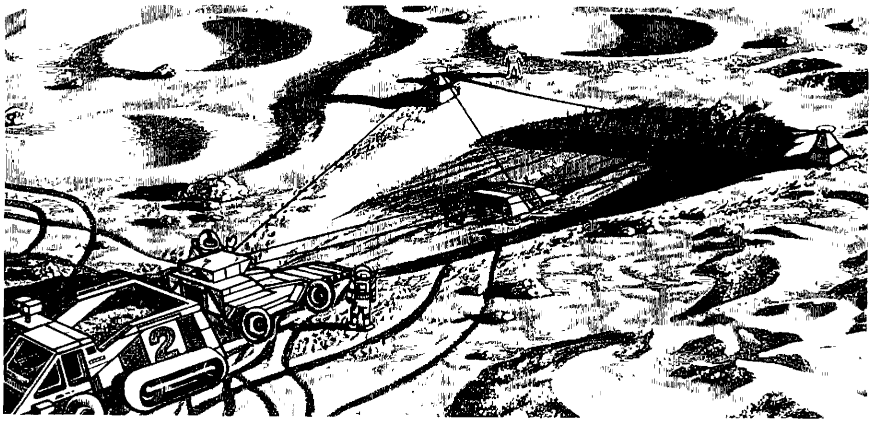


Figure 24

Three-Drum Slusher

This lunar mining system is called a "three-drum slusher." It is similar to a simple two-drum dragline, in which a bucket is pulled by cables to scrape up surface material and dump it into a waiting truck. The third drum allows the bucket to be moved from side to side to enlarge the mining pit. Surface mining of unconsolidated lunar regolith, using versions of draglines or front-end loaders, will probably be done at a lunar base initially, although deeper "bedrock" mining is also a possibility and underground mining may even be attractive if appropriate resources are located



missions would place heavy emphasis on the processing of mineral ores in space to recover useful metals, while others would place a premium on processing techniques aimed at the recovery of oxygen and hydrogen. Technologies in mining, materials handling, chemical extraction, storage, and manufacturing are applicable to various resources. Early development of these common technologies can improve the performance of the transportation, energy, and other systems.

Communications

Communications technology has already proven its worth and is at a relatively advanced stage of development. But further technological advances are possible in coupling communications equipment to computers, in developing large communication platforms in space, and in increasing the power and defining the focus of transmissions from space.

The economic, social, and political potential for worldwide applications of communications technology, particularly in Third World countries, is very great and should not be overlooked. Incremental advances in existing technologies should be sufficient to handle the communication and computing aspects, but the sociopolitical problems involved in creating an enhanced global communications network are of a different order and beyond the scope of the present report.

New Technologies

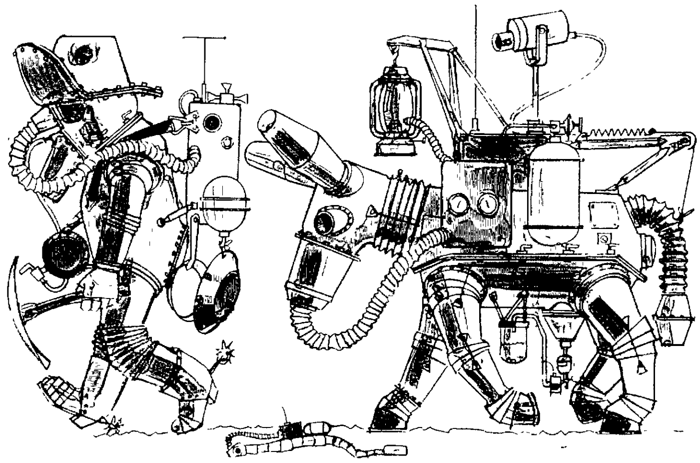
We can take for granted that new methods and machines will be needed to adapt known techniques to operations in space. This almost amounts to a general principle: Old technologies will require new technologies in order to be applied in space (see fig. 25). What these needs may be cannot be known in advance, but allowances should be made to provide for them. Otherwise, time and cost overruns will inevitably result.

In this same vein, we should recognize that the development of entirely new technologies, such as those needed to effect weather/ climate control, atmospheric cleanup, or purging of the ionosphere, may prove to be desirable. These are massive undertakings and yet they cannot be disregarded. Like nearly continuous remote sensing of and almost instant communication with any point on Earth, these climate-control technologies are of enormous potential benefit to humankind. In the end, the successful accomplishment of any one of them could justify the entire space program.

Figure 25

Lunar Prospector?

One approach to the lunar environment is to simply modify old technologies somewhat to fit the new conditions. Here, that approach is taken to the extreme in this lunar resource prospecting system. The other extreme is to develop totally new technology, such as a completely automated expert system for lunar prospecting. The most workable approach is probably a compromise between old technology and new technology, using the best of both. What elements of this "old technology" are likely to be found at a lunar base in 2010?



Issues for Further Study

Hubert Davis

Overview

The mind-expanding nature of our future activities beyond Earth leads to a plentiful flow of new ideas and major improvements on earlier concepts. The recent discovery of numerous Earth-crossing asteroids, for example, adds greatly to the magnitude and diversity of the material resources in space of which we are aware. However, a serious question arises. Does there exist any orderly process for gaining general awareness of these new ideas or for evaluating their importance to society? Membership in a specific academic, government, or industrial group, coupled with persistence and eloquence, are today's means of hearing and being heard. These mechanisms may not, however, be the optimal means for flushing out and eventually implementing the best new ideas.

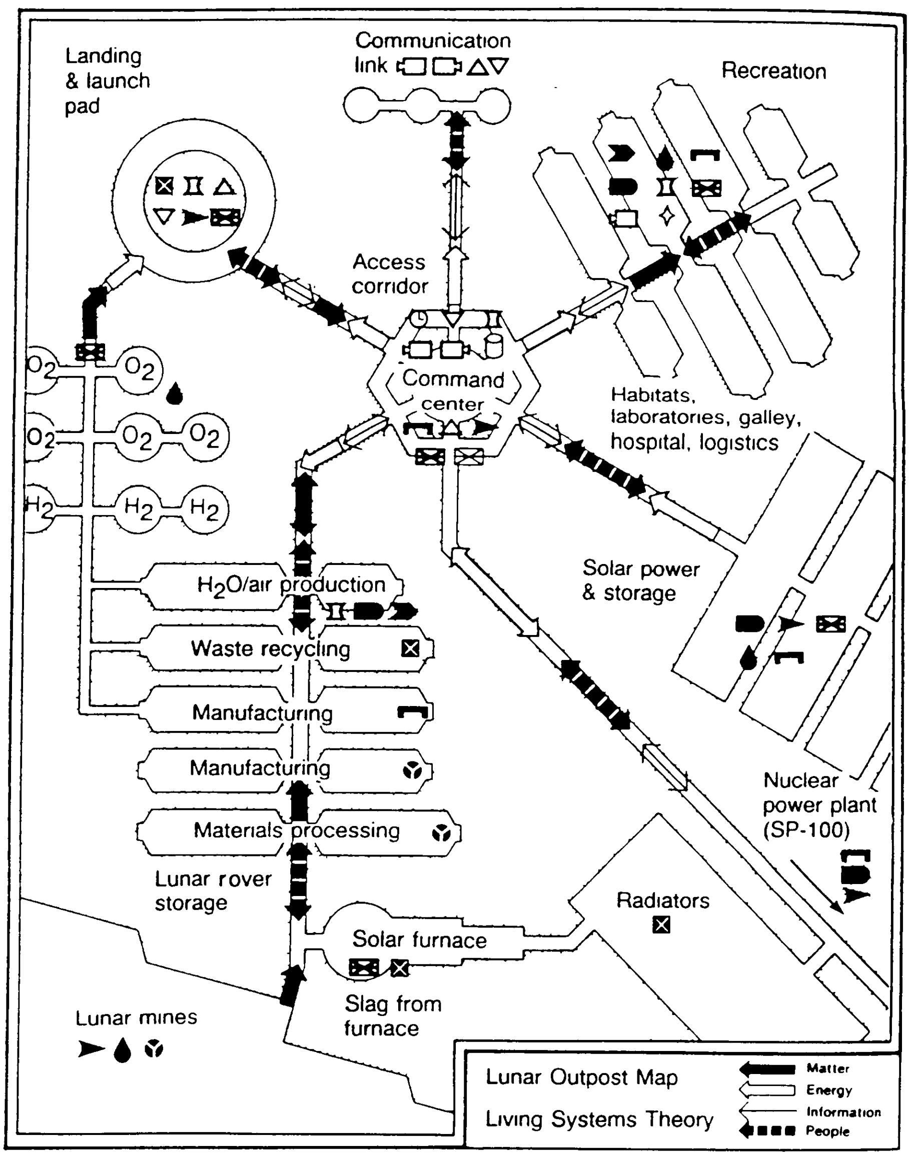
One small step toward achieving the goal of preserving for use the best of the suggested new concepts is the "systems study" approach. In this approach, a set of future needs and a straightforward means of satisfying these needs are described in quantitative terms as a "scenario." This scenario is then set forth as a benchmark case for testing the relative merit of new, alternative means of meeting one or more of these needs. This systems approach should be used to assess the merits of new concepts and to identify the most important advancements in technology needed to establish or enhance the merit of the concept. (The map of a lunar outpost illustrates the application of another kind of systematic study, known as "general living systems" theory and analysis.)

Ideally, as needs change and new concepts and data become available, the "baseline" scenario should be revised to incorporate some of the new ideas. When that occurs, the technology development of the newly incorporated approaches should actively begin to remove residual uncertainties. But the effort should, in most cases, stop short of "prototyping."

It is very important to remain as generic or flexible as practical in order to be ready to adapt the scenarios and associated technologies to changes in the social norms, political climate, and economic health of the nation.

To further complicate matters, once a new "baseline" scenario is accepted for testing of new concepts, earlier conclusions must also be reexamined since former "new" ideas that were earlier rejected may be found to be highly desirable given the new scenario.

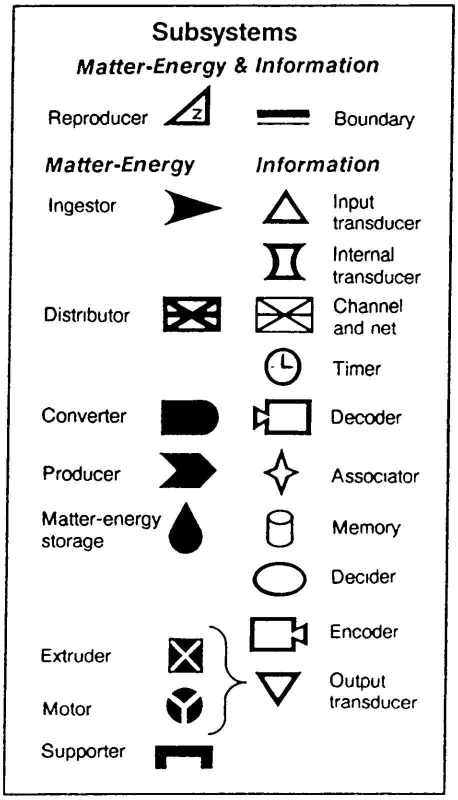
Some formalized means should be found for establishing, testing and refining, utilizing and maintaining


Landing
& launch
pad
Communication
link
Recreation
Access
corridor
Command
center
Habitats,
laboratories, galley,
hospital, logistics
Solar power
& storage
H_2O/air production
Waste recycling
Manufacturing
Manufacturing
Materials processing
Lunar rover
storage
Solar furnace
Slag from
furnace
Nuclear
power plant
(SP-100)
Radiators
Lunar mines
Lunar Outpost Map
Living Systems Theory
Matter
Energy
Information
People

Lunar Outpost Map

General living systems theory is a conceptual integration of biological and social approaches to the study of living systems. Living systems are open systems that input, process, and output matter and energy, as well as information which guides and controls all their parts. In human organizations, in addition to matter and energy flows, there are flows of personnel, which involve both matter and energy but also include information stored in each person's memory. There are two types of information flows in organizations: human and machine communications and money or money equivalents. Twenty subsystem processes dealing with these flows are essential for survival of systems at all levels.

The general procedure for analyzing such systems is to map them in two- or three-dimensional space. This map of a lunar outpost indicates its subsystems and the major flows within it. Such an analysis would take into account the primary needs of human systems—foraging for food and other necessary forms of matter and energy; feeding; fighting against environmental threats and stresses; fleeing from environmental dangers; and, in organizations which provide a comfortable, long-term habitat, perhaps reproducing the species. This study would analyze the effects on human social and individual behavior of such factors as weightlessness or 1/6 gravity; limited oxygen and water supplies; extreme temperatures; available light, heat, and power; varying patterns of light and dark; and so forth. A data bank or handbook could be developed of the values of multiple variables in each of the 20 subsystems of such a social system.



a baseline scenario of long-range space activities and of supporting, refereeing, and reviewing the application of this scenario in system studies of new concepts. This process was begun by NASA's Office of Aeronautics and Space Technology (OAST) in the mid-1970s, but it was abandoned in the late 1970s because of budgetary constraints and the press of nearer term needs, as perceived by NASA management. Total cost to NASA of restoring and enhancing these efforts would be only 0.01-0.02 percent of NASA's yearly budget.*

* Since this report was drafted, significant long-term planning activities have been undertaken, initiated by the work of the National Commission on Space. The commission's report, *Pioneering the Space Frontier*, is available from Bantam Press.

Lunar Resource Utilization

Resource Prospecting

Early priority should be given to an automated lunar polar spacecraft to perform a global survey of the Moon with instruments appropriate to detect the presence, location, and concentration of useful materials. This mission may have to be repeated or extended to follow up on areas of particular scientific and economic interest.

Lunar Assay

Automated surface rovers, with the capabilities of coring, assaying materials, and possibly returning samples to Earth, should be sent out to gather data. This activity should be completed several years before final commitment is made to the location of the initial lunar base. (See figure 26.)

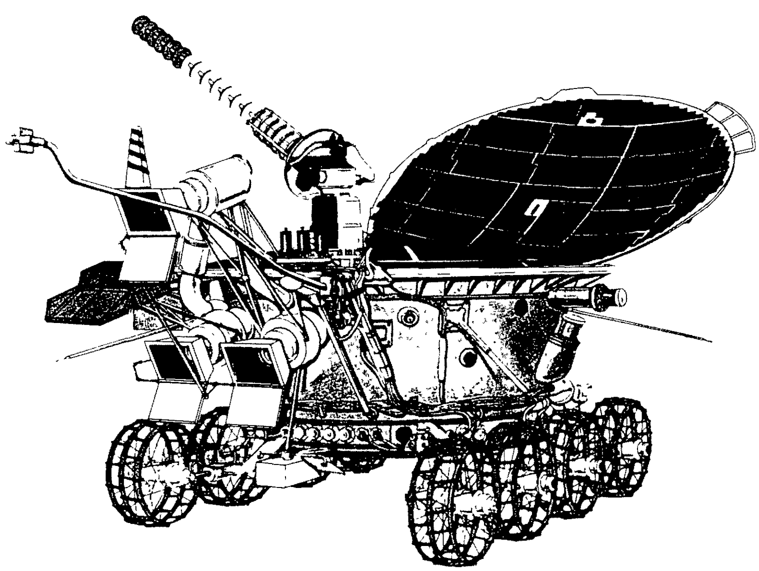


Figure 26

Lunokhod 1 and Apollo 17 Rover

a. Automated vehicles roving over another planetary body were first used in the early 1970s by the Soviets on their Lunokhod missions. These lunokhods were capable of traveling tens of kilometers at speeds up to 2 km/hr. They were run from a Soviet control center by a crew of five—commander, driver, navigator, operator, and onboard-systems engineer. The crew used television images and systems readouts to drive and operate the vehicles. The lunokhods carried several scientific instruments, including an x-ray fluorescence spectrometer for determining the chemical composition of lunar regolith. Lunokhod 1 traveled about 10 km and Lunokhod 2 traveled 37 km, each over a period of months.

Lunar Mining

Mining the Moon will present new challenges. Surface mining will probably be the norm, although subsurface mining may be necessary in some cases. The movement of large amounts of material will degrade the scientific utility of the mining site, alter its appearance, and release gases into the tenuous lunar atmosphere. Thus, the effect of lunar mining on the environment will have to be carefully evaluated before mining begins.

Process Development

Ideas for getting oxygen from lunar materials have been generated since the 1960s and '70s.* Now, preliminary design studies and process engineering should

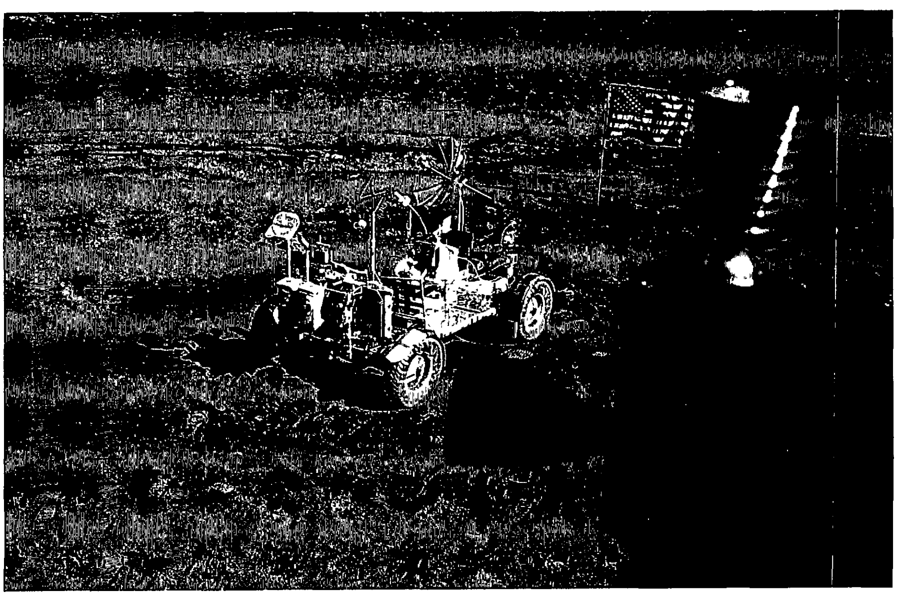
* See, for example,

Rosenberg, S. D.; G. A. Guter; and F. E. Miller. 1964. The On-Site Manufacture of Propellant Oxygen Utilizing Lunar Resources. Chem. Eng. Prog. **62**:228-234.

Rosenberg, S. D.; G. A. Guter; and F. E. Miller. 1965. Manufacture of Oxygen from Lunar Materials. Ann. N.Y. Acad. Sci. **123**:1106-1122.

McKay, David S., and Richard J. Williams. 1979. A Geologic Assessment of Potential Lunar Ores. In Space Resources and Space Settlements, NASA SP-428, pp. 243-255.

Rao, D. Bhogeswara; U. V. Choudary; T. E. Erstfeld; R. J. Williams; and Y. A. Chang. 1979. Extraction Processes for the Production of Aluminum, Titanium, Iron, Magnesium, and Oxygen from Nonterrestrial Sources. In Space Resources and Space Settlements, NASA SP-428, pp. 257-274 .



b. The Rover was used on Apollo missions 15, 16, and 17. Here, the Apollo 17 Rover is seen near the Lunar Module. While not intended for automated operations, the basic rover systems (motors, power, communication, TV, steering and control) could easily be adapted to unmanned exploration traverses. Experience gained in the design and operation of the Apollo Rover, combined with the Soviet Lunokhod experience, will provide a basis for future lunar and martian rover designs.

be performed to derive a comprehensive plan involving laboratory experimentation, bench testing, and pilot plant development for the purpose of testing, developing, and refining the beneficiation and feedstock conversion steps necessary to produce useful products from lunar regolith material. (See figure 27.) This plan should permit examination and quantification of the optimal conversion pressure, temperature, and concentration, conversion efficiency, energy requirements, heat rejection, catalysts, carrier fluid consumption, and the scale effects so as to allow confident design of an operational chemical plant.

Ancillary Equipment Development

Equipment for automated mobility; solid material conveyance; feedstock material insertion and extraction (into and from the converter); water vapor condensation; electrolysis; gaseous oxygen and hydrogen refinement, movement, and storage; oxygen liquefaction; liquid oxygen storage and transport; and other purposes must be conceptualized, designed, tested, and developed for the minimum

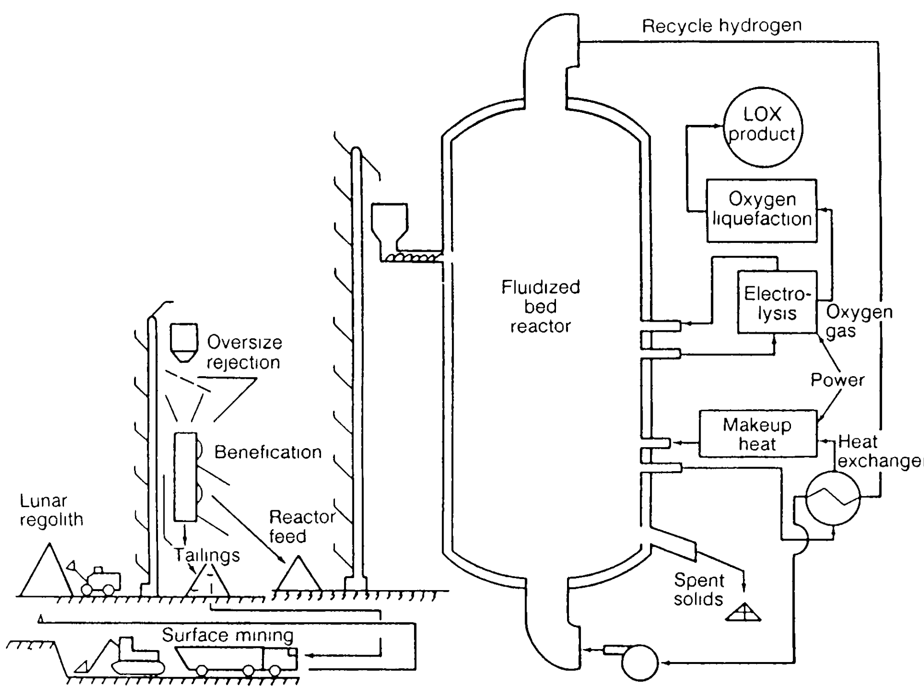


Figure 27

Oxygen From Lunar Ilmenite

In this concept for a lunar oxygen plant, ilmenite ($FeTiO_3$) is concentrated from lunar regolith and then fed into a three-stage fluidized bed. In the upper stage, the ilmenite concentrate is preheated by hot hydrogen passing through the powdered ilmenite. The hot ilmenite then goes into the second stage, which is the main reactor bed. Here, even hotter hydrogen reacts with the ilmenite, extracting one oxygen atom from each ilmenite molecule, forming H_2O, metallic iron (Fe), and TiO_2. The H_2O and excess hydrogen are extracted and circulated through an electrolyzer, which breaks down the H_2O. The released oxygen is then cooled, compressed, and stored as liquefied oxygen. The spent feedstock enters the third stage, where heat is extracted by hydrogen gas before the spent material is dumped from the reactor.

of human intervention. (See figure 28.)

A virtue of these activities is that each of these elements is individually a rather straightforward application of advanced automatic or teleoperative technology. And with the appropriate mix of this technology and the human element, the optimal manufacturing capacity can be placed on the Moon.

Development of Space Transportation Equipment

Large, automated orbital transfer vehicles and lunar landing vehicles must be better defined before we can quantify performance, life, and cost factors. Numerous technology developments will be needed before we can confidently begin full-scale development. The key technologies of these vehicles appear to be the following.

High performance oxygen/ hydrogen rocket engine: A new-generation rocket engine will be needed early. It should generate higher specific impulse than current engines (480-490 sec, as compared to 446 sec for the RL-10), produce a thrust of approximately 7500 lbf, provide moderate throttling capability, and be designed for long life with maintenance in space.

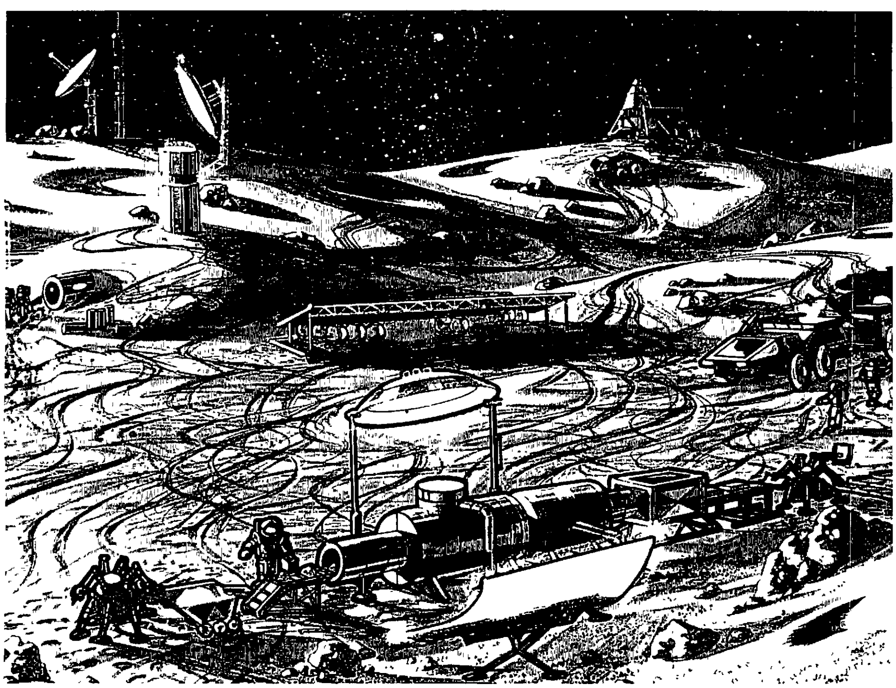


Figure 28

Ancillary Equipment at a Lunar Base

This lunar base sketch illustrates some of the ancillary systems that are necessary for a productive lunar base. The sketch includes a mining system, a processing plant, a construction-block-making unit, a solar power generator, a buried habitat and agricultural unit with solar lighting reflector, automated materials handling equipment, cryogenic storage tanks, surface transportation vehicles, communication antennas, and a rocket system for transportation to lunar orbit. All of these systems require technology development.

Owing to these requirements, an advanced space engine will have to be designed for a very high chamber pressure (1500-2000 psia) and a high expansion ratio (2000:1). (See figure 29.)

Cryogenic propellant handling and preservation: The ability to store, transfer, measure, and condition cryogenic fluids (including liquid oxygen, hydrogen, and argon) with zero loss requires extensive development and testing. (See figure 30.)

Aerobraking technology: Although theoretically very attractive for returning payloads to LEO, many uncertainties, including aerobraking equipment mass, must be resolved before aerobraking is practiced. (See figure 31.) Advanced concepts in guidance, navigation, and control will need investigation, particularly for uses that involve higher velocity return to Earth orbit. Early Shuttle-launched test missions should be considered.

Advanced composite structures: Overall spacecraft systems design using advanced composite structures requires data on micrometeoroid impact effects, cryogenic fluid compatibility, equipment attachment, inspection and repair, and other aspects.

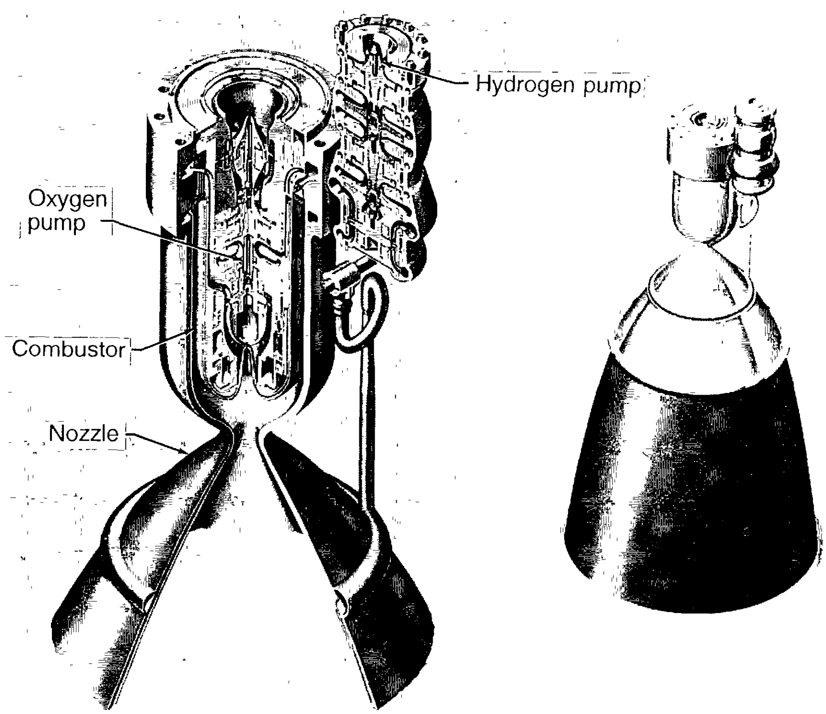


Figure 29

Advanced Engine

New, high performance engines for orbital transfer vehicles must be developed. Here is an oxygen-hydrogen engine concept developed by Aerojet TechSystems Company specifically for use in a reusable orbital transfer vehicle designed to shuttle between low Earth orbit and either geosynchronous Earth orbit or lunar orbit.

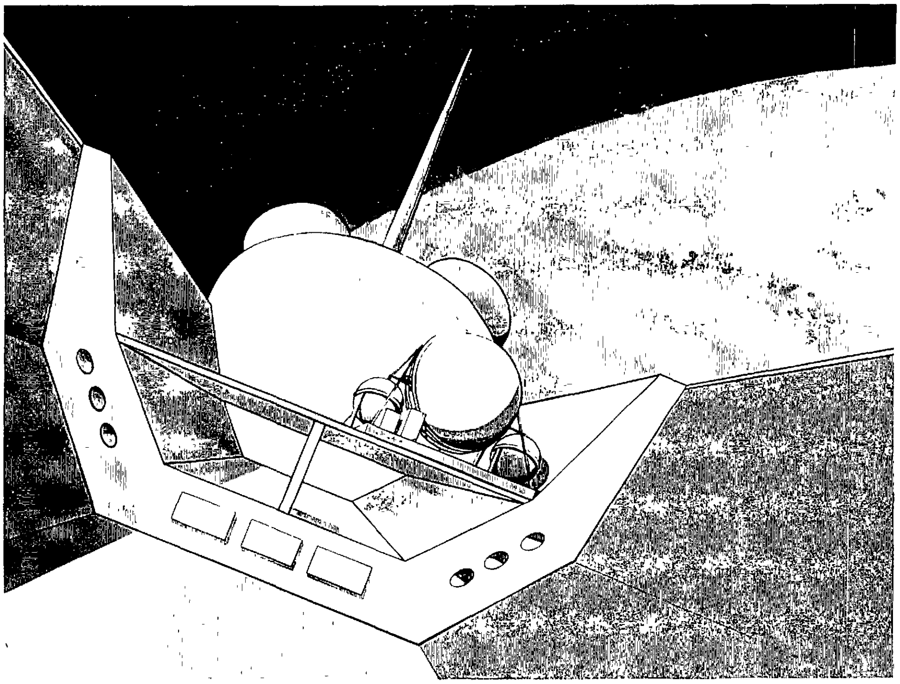


Figure 30

Cryogenics

Technology must be developed and tested for complex space operations. Here is a sketch of a proposed cryogenic fluid management experiment, which will test on the Shuttle orbiter some of the necessary equipment to transport, transfer, measure, and store cryogenic fluids in space. This technology is needed to make reusable orbital transfer vehicles and lunar landers practical. Cryogenic handling technology is also critical to future space operations that make use of lunar-provided rocket propellant.

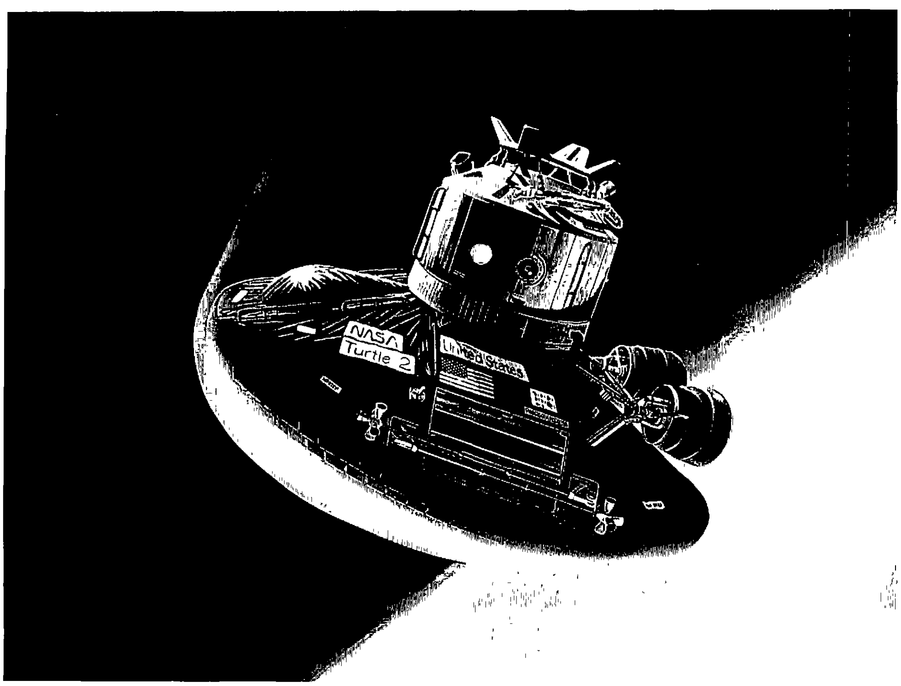


Figure 31

Aerobraking Technology

Aerobraking technology must be developed before efficient transfer can be made from lunar or geosynchronous orbit to low Earth orbit. Aerobraking is also necessary for any Mars return mission, whether manned or unmanned. Without aerobraking, considerable rocket propellant must be used to slow down a spacecraft coming toward the Earth. Here is an aerobrake on an orbital transfer vehicle returning from lunar orbit. The aerobrake uses friction with the Earth's uppermost atmosphere to slow down the vehicle and divert it to a low Earth orbit. This procedure requires a combination of very heat resistant brake surfaces, precisely known aerodynamic properties, and very careful trajectory and attitude control.

Artist: Pat Rawlings

Operations technology: The infant art and science of maintaining, servicing, storing, and checking out complex space vehicles (both manned and automated) whose entire service life is spent in the space environment requires nurturing. (See figure 32.) Many facets of this problem require both hardware and software development. A design goal of operations technology must be efficiency. Current operation procedures for the Space Shuttle are so costly that, if applied directly to reusable orbital transfer vehicles, they could invalidate the cost-savings potential of these vehicles over expendable vehicles.

Debris control, collection, and recycling: Our future operations in space must not litter. Active measures are needed to prevent littering. A plan of action is needed to remove discarded objects from valuable space "real estate." (See figure 33.) And the technology for recycling waste materials in space needs to be developed. The Shuttle external tank represents a resource in space which can be employed—perhaps early in the space station

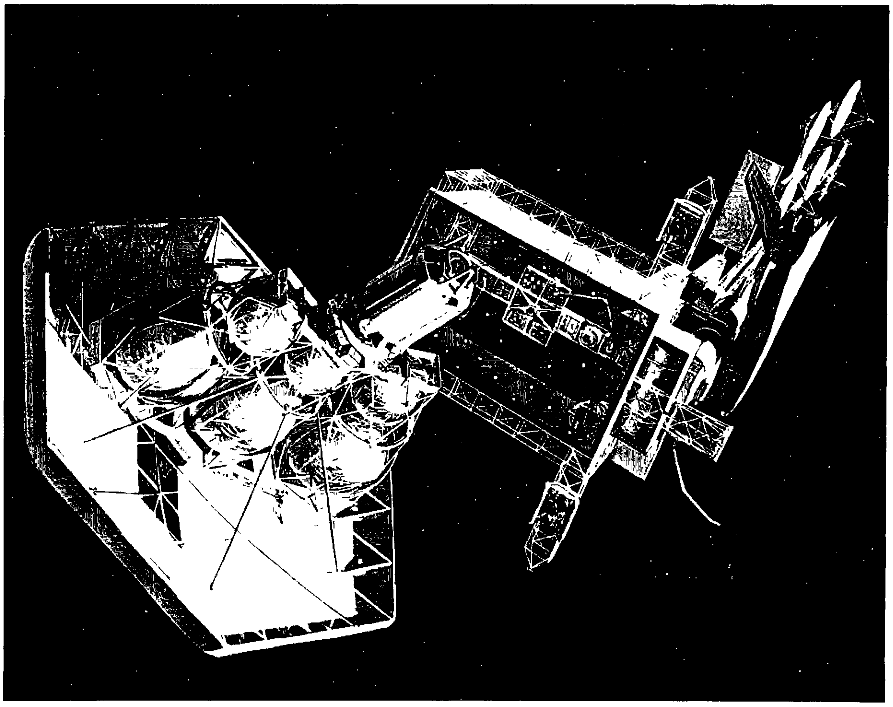
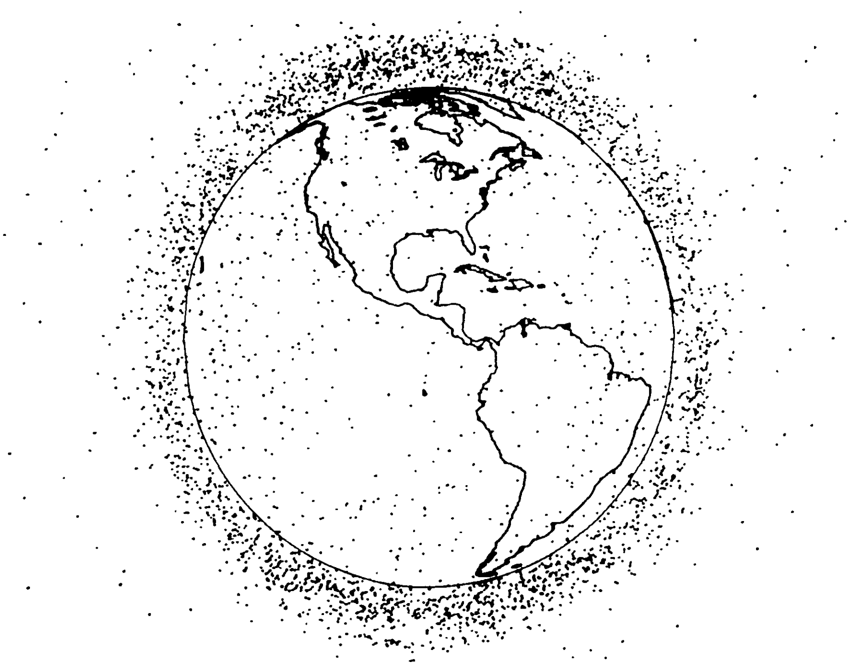


Figure 32

Space Servicing

As the hardware for complex space operations is developed, the technology for maintaining complex hardware in space must also be developed. Here is a General Dynamics concept for a space hangar and maintenance facility associated with the space station. This facility can be used to refuel, service, and repair the orbital transfer vehicle shown in the foreground.



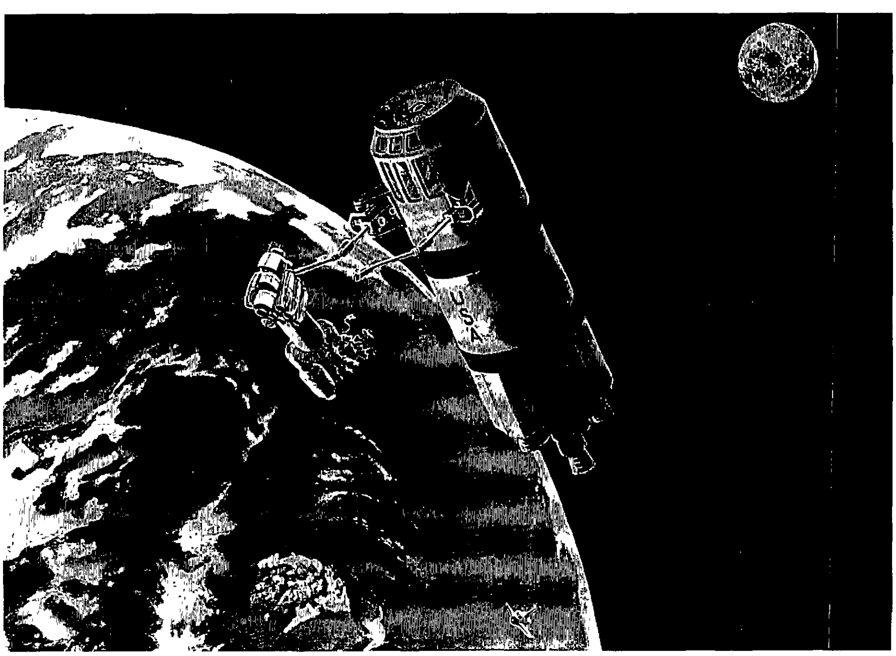


Figure 33

Orbital Debris

Orbital debris is a growing problem, which will require more and more attention as space operations increase in volume. Above is a map showing all the objects larger than 10 cm (baseball size) that were found in low Earth orbit by the U.S. Space Command on May 30, 1987. (The size of the objects is, of course, not to scale on this map; if it were, they could not be seen.) Most of these objects are spent rocket stages, dead satellites, and fragments from the breakup of old spacecraft. The map emphasizes the need to minimize new sources of orbital debris and even to clean up existing debris using "debris sweepers." A satellite designed to capture large pieces of orbital debris is shown below the map.

Artist: Ray Bruneau

program. Thirty tons of aluminum structure available at negligible cost in LEO is simply too valuable to be discarded.

Asteroid Resource Utilization

The first step in asteroid utilization is making an inventory. Advanced Earth-based observation techniques and equipment can be economically fielded to gain quantum improvements in our knowledge of the number, orbits, size, composition, and physical properties of the Earth-crossing asteroids (see table 9). A subset of those asteroids inventoried might be further examined by spaceborne instruments with capabilities similar to those of the proposed Mars geochemical mapper (see fig. 34). A smaller subset might be identified as candidates for surface exploration and pilot plant operation.

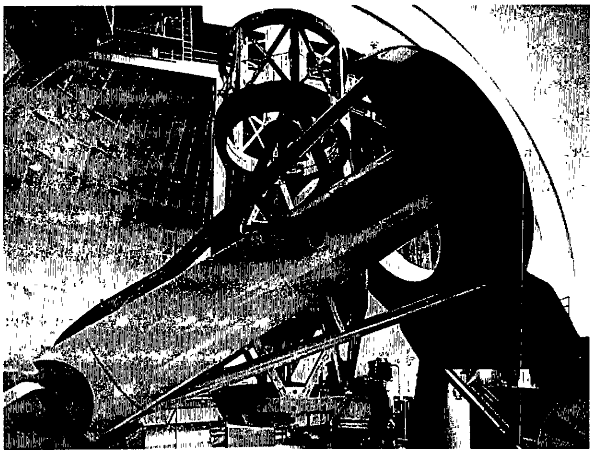
In parallel, advanced space propulsion and mission design techniques should be applied to come to understand the logistics for exploiting this potential space resource.

Space Energy Utilization

The petroleum crisis of the 1970s was not an anomalous, singular event. Even in the face of very effective energy conservation and increased petroleum exploration, the problem will return in the near future. The nearly infinite furnace of the Sun must eventually be used to provide the dominant portion of human beings' energy needs. Space is the best place to harvest and convert sunlight into more concentrated, continuous, and useful forms. Studies on the solar power satellite, a network of solar reflectors, and other means of enhancing the utility of sunlight on Earth should continue. However, the studies should be expanded to include use of such systems to provide energy from space *in* space.

Space "Real Estate" Utilization

If material and energy resources were both abundant and accessible to people, numerous human endeavors exploiting the attributes of space (nearly perfect vacuum, microgravity, and vantage point) would begin and greatly expand.



Mt. Palomar's 200-inch Hale Telescope, pointing to the zenith, as seen from the east side.

TABLE 9. *Physical Parameters of 17 Near-Earth Asteroids**

Name	*Diameter, km*	*Semimajor axis of its orbit, astronomical units*	*Orbital eccentricity*	*Inclination of its orbit, degrees from the plane of the ecliptic*
433 Eros	39.3 x 16.1[a]	1.458	0.219	10.77
887 Alinda	3.6[b]	2.50	.55	9.19
1036 Ganymed		2.66	.54	26.45
1566 Icarus	1.04[d]	1.08	.83	22.91
1580 Betulia	6.3[f]	2.19	.49	52.04
1620 Geographos	2.4[g]	1.24	.34	13.33
1627 Ivar	6.2[h]	1.86	.40	8.44
1685 Toro	5.6[i]	1.36	.44	9.37
1862 Apollo	1.2-1.5 ± 0.1[j]	1.47	.56	6.26
1865 Cerberus		1.08	.47	16.09
1915 Quetzalcoatl	0.14[h]	2.53	.58	20.5
1943 Anteros	2.0[k]	1.43	.26	8.7
2100 Ra-Shalom	>1.4[l]	0.83	.44	15.7
2201 Oljato		2.18	.71	2.5
1979 VA		2.5	.61	2.7
1980 AA		1.86	.43	4.1
1981 QA		2.35	.49	8 95

[a] Lebofsky and Rieke (1979).
[b] Zellner and Gradie (1976).
[d] Gehrels et al. (1970).
[f] Tedesco et al. (1978).
[g] Dunlap (1974).
[h] G. J. Veeder (personal communication).
[i] Dunlap et al. (1973).
[j] Lebofsky et al. (1981).
[k] Revised from Veeder et al. (1981; personal communication).
[l] Lebofsky (personal communication).

* After Lucy A. McFadden, Michael J. Gaffey, and Thomas B. McCord, 1984, Mineralogical-Petrological Characterization of Near-Earth Asteroids, Icarus **59**:25-40.

The communication relay function from GEO is only the first of an infinite series of useful and economically valuable activities in space. The ability to observe activities on Earth and, if necessary, to intervene in events may prove to be the means by which nuclear technology is reconfigured to benefit humankind rather than to threaten our existence.

Space as a place to go to and later as a place to live and work in will become of increasing importance in the decades to come. It is not too early to consider growth from NASA's 8- to 12-person space station to communities 2 or 3 orders of magnitude larger (see fig. 35). Life support technology will need to progress from merely preserving respiratory functions with some small degree of mobility for a handful of exceptional, highly trained people to providing comfortable and even luxurious accommodations for ordinary human beings at work, at school, or at leisure. (See figure 36.)

The potential of personally working and residing in space is perhaps

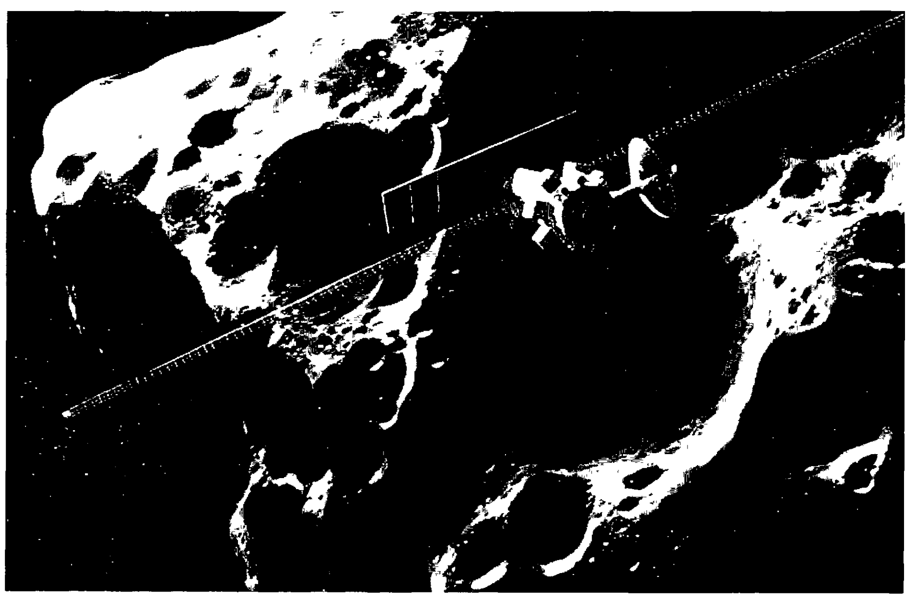


Figure 34

An Artist's Conception of an Unmanned Spacecraft Mission to an Asteroid

An unmanned spacecraft could make detailed photos of an asteroid and chemically map it in preparation for later automated mining missions.

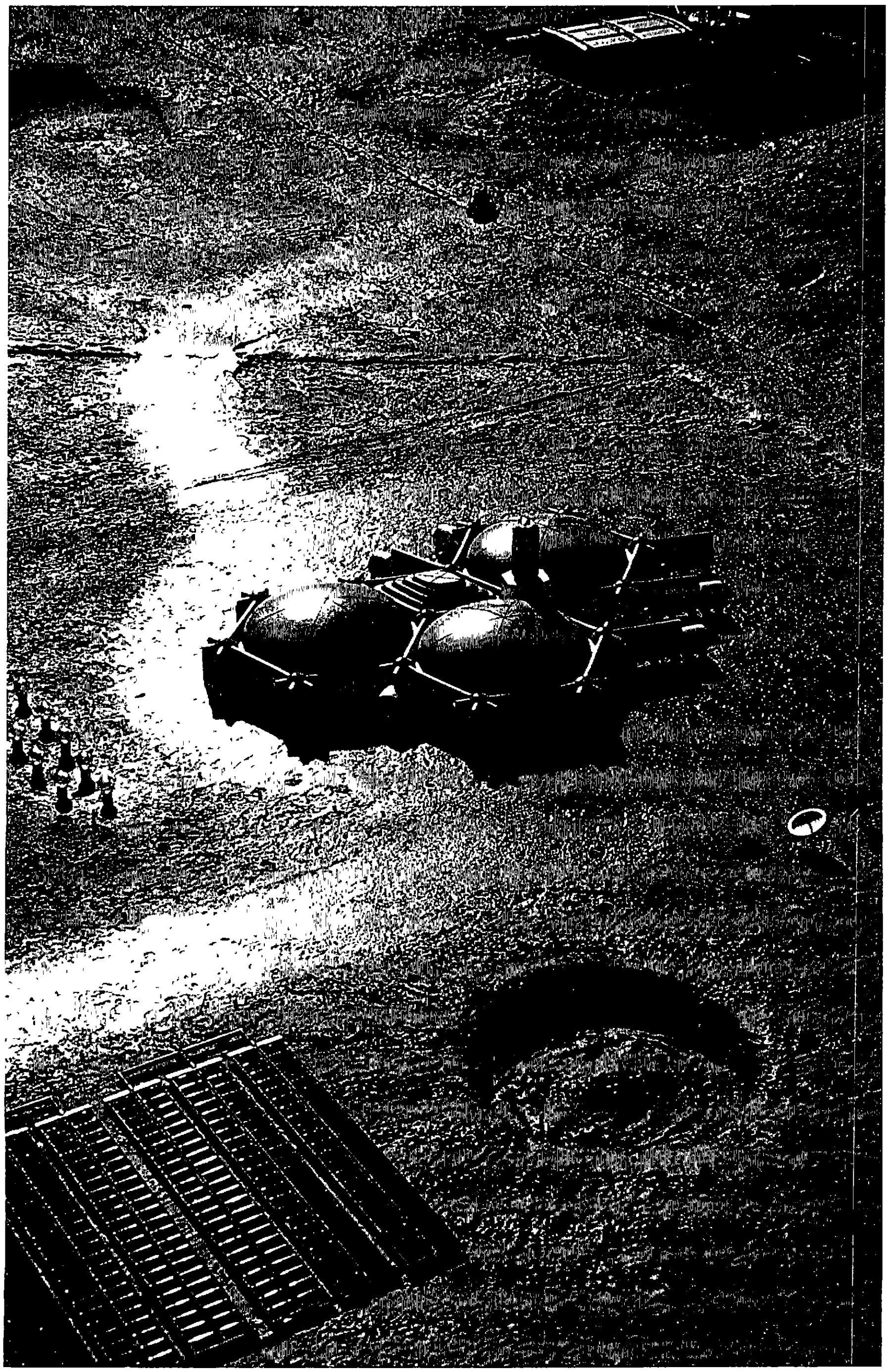


Figure 35

Architectural Model of a Moon Base

This model is the product of a recent study by a group at the University of Houston's College of Architecture. The lunar base, designed for 28 people, includes both inflatable domes and hardened modules. The three functional areas of the base are for habitation, laboratory use, and agriculture.

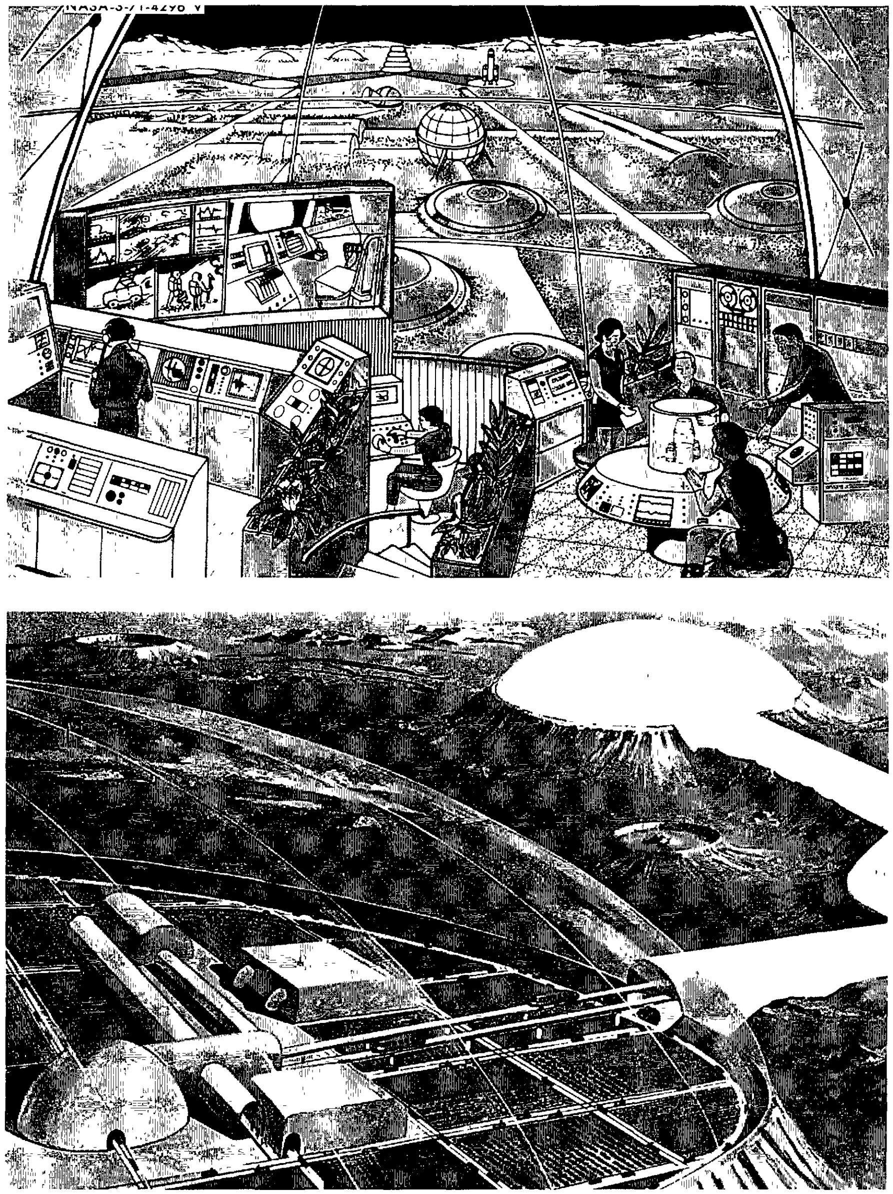
Figure 36

Advanced Lunar Bases

Eventually lunar bases will grow in both the number of people living there and the complexity and diversity of their activities.

In the top illustration, a lunar base capable of supporting several hundred people stretches out across the lunar landscape. This control center can be used to monitor various exploration and transportation activities. Residents may not be satisfied with video images or periscope views of their lunar surroundings and may, like their Mercury astronaut predecessors, insist on windows. Windows could be made thick and dense enough to provide protection from normal radiation, and lead shutters could be used during a solar flare

In an even more advanced lunar base (bottom), large-scale networks of interconnected domes may house large farms, factories, and living areas These domes may have Earth-like atmospheres Currently, radiation hazards from solar flares and cosmic rays would seem to make this kind of planetary engineering for human habitation impractical, but technologies to deflect this radiation or to make humans less susceptible to it may eventually be developed to enable humans to live in large domes on the lunar surface (or on the surface of Mars).

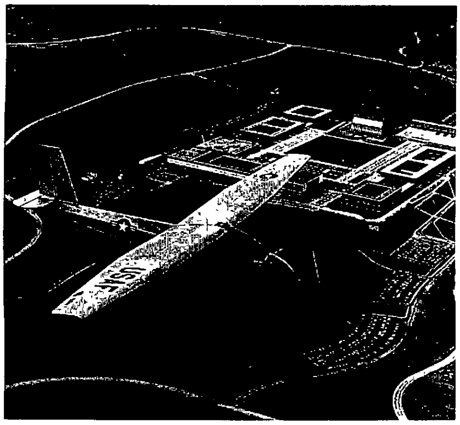


the strongest single motivation for young people to excel. And it is important to the development of productive future generations—motivated and trained to prove totally incorrect the gloomy "fixed sum game" scenarios for humankind's future. Needed are effective and serious technical and sociological studies, artistic representation of space architectures at both small and large scale, and use of the media to portray people's future in space more realistically as productive and peaceful rather than universally warlike and destructive.

In viewing works like *Star Trek* and *Star Wars*, we must wonder what precursor society and organization *built* the wonderful artifacts so wantonly destroyed in an hour or two. Some of us would be much more interested in the character and adventures of the *builders* than we are in those of the desperate defenders and destroyers. We think many young people might share our preferences.

One final thought: A Space Academy patterned after the military academies might be a very worthwhile national investment (see fig. 37). This academy might best be a 4- to 6-year institution which took in new students who had successfully completed 2 years of undergraduate work. The last 2 or 3 years might send some of the semifinished products into distinguished universities to gain their Ph.D.s under noted scholars, scientists, and engineers who had contributed to the state of the art in space.

Congressional appointments, paid tuition and salary, assured career entry, and other attributes of the service academies should be characteristics of this institution. A generation of fully prepared people is much more important than hardware or brick and mortar.



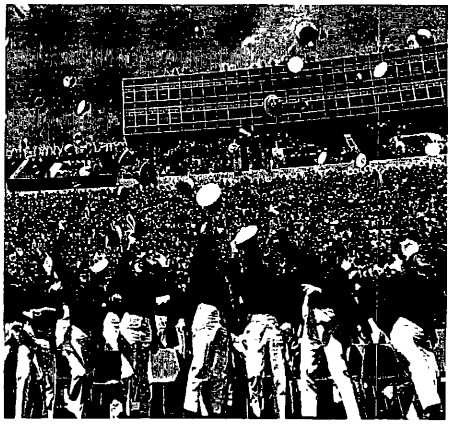


Figure 37

Space Academy

A space academy may be an effective way to prepare Americans for living and working in space. Here are views of the Air Force Academy in Colorado Springs and the graduating Air Force cadets. Graduates of a space academy would have the required technical training, the organizational training, and the motivation to be the leaders in future major space projects, including lunar base development, space infrastructure growth, and eventually Mars settlements

Sightseeing

Other optimistic visions of the future of space activities might include extensive tourism. Here, from a scenic lookout point on Mars, is a tourist's view of the Valles Marineris, the longest, deepest, and most spectacular canyon in the solar system. The idea that much of the solar system might eventually be available for anyone to visit is clearly a visionary one, but one that is not beyond the reach of projected advances in technology.

Addendum: Participants

The managers of the 1984 summer study were

David S. McKay, Summer Study Co-Director and Workshop Manager
Lyndon B. Johnson Space Center

Stewart Nozette, Summer Study Co-Director
California Space Institute

James Arnold, Director
of the California Space Institute

Stanley R. Sadin, Summer Study Sponsor
for the Office of Aeronautics and Space Technology
NASA Headquarters

Those who participated in the 10-week summer study as faculty fellows were the following:

James D. Burke	Jet Propulsion Laboratory
James L. Carter	University of Texas, Dallas
David R. Criswell	California Space Institute
Carolyn Dry	Virginia Polytechnic Institute
Rocco Fazzolare	University of Arizona
Tom W. Fogwell	Texas A & M University
Michael J. Gaffey	Rensselaer Polytechnic Institute
Nathan C. Goldman	University of Texas, Austin
Philip R. Harris	California Space Institute
Karl R. Johansson	North Texas State University
Elbert A. King	University of Houston, University Park
Jesa Kreiner	California State University, Fullerton
John S. Lewis	University of Arizona
Robert H. Lewis	Washington University, St. Louis
William Lewis	Clemson University
James Grier Miller	University of California, Los Angeles
Sankar Sastri	New York City Technical College
Michele Small	California Space Institute

Participants in the 1-week workshops included the following:

Constance F. Acton	Bechtel Power Corp.
William N. Agosto	Lunar Industries, Inc.
A. Edward Bence	Exxon Mineral Company
Edward Bock	General Dynamics
David F. Bowersox	Los Alamos National Laboratory
Henry W. Brandhorst, Jr.	NASA Lewis Research Center
David Buden	NASA Headquarters
Edmund J. Conway	NASA Langley Research Center
Gene Corley	Portland Cement Association
Hubert Davis	Eagle Engineering
Michael B. Duke	NASA Johnson Space Center
Charles H. Eldred	NASA Langley Research Center
Greg Fawkes	Pegasus Software
Ben R. Finney	University of Hawaii
Philip W Garrison	Jet Propulsion Laboratory
Richard E. Gertsch	Colorado School of Mines
Mark Giampapa	University of Arizona
Charles E. Glass	University of Arizona
Charles L. Gould	Rockwell International
Joel S. Greenberg	Princeton Synergetics, Inc.
Larry A. Haskin	Washington University, St. Louis
Abe Hertzberg	University of Washington
Walter J. Hickel	Yukon Pacific
Christian W. Knudsen	Carbotek, Inc.
Eugene Konecci	University of Texas, Austin
George Kozmetsky	University of Texas, Austin
John Landis	Stone & Webster Engineering Corp.
T. D. Lin	Construction Technology Laboratories
John M. Logsdon	George Washington University
Ronald Maehl	RCA Astro-Electronics
Thomas T. Meek	Los Alamos National Laboratory
Wendell W. Mendell	NASA Johnson Space Center
George Mueller	Consultant
Kathleen J. Murphy	Consultant
Barney B. Roberts	NASA Johnson Space Center
Sanders D. Rosenberg	Aerojet TechSystems Company
Robert Salkeld	Consultant
Donald R. Saxton	NASA Marshall Space Flight Center
James M. Shoji	Rockwell International
Michael C. Simon	General Dynamics
William R. Snow	Electromagnetic Launch Research, Inc.
Robert L. Staehle	Jet Propulsion Laboratory
Frank W. Stephenson, Jr.	NASA Headquarters
Wolfgang Steurer	Jet Propulsion Laboratory
Richard Tangum	University of Texas, San Antonio
Mead Treadwell	Yukon Pacific
Terry Triffet	University of Arizona
J. Peter Vajk	Consultant
Jesco von Puttkamer	NASA Headquarters
Scott Webster	Orbital Systems Company
Gordon R. Woodcock	Boeing Aerospace Company

The following people participated in the summer study as guest speakers and consultants:

Edwin E. "Buzz" Aldrin	Research & Engineering Consultants
Rudi Beichel	Aerojet TechSystems Company
David G. Brin	California Space Institute
Joseph A. Carroll	California Space Institute
Manuel I. Cruz	Jet Propulsion Laboratory
Andrew H. Cutler	California Space Institute
Christopher England	Engineering Research Group
Edward A. Gabris	NASA Headquarters
Peter Hammerling	LaJolla Institute
Eleanor F. Helin	Jet Propulsion Laboratory
Nicholas Johnson	Teledyne Brown Engineering
Joseph P. Kerwin	NASA Johnson Space Center
Joseph P. Loftus	NASA Johnson Space Center
Budd Love	Consultant
John J. Martin	NASA Headquarters
John Meson	Defense Advanced Research Projects Agency
Tom Meyer	Boulder Center for Science and Policy
John C. Niehoff	Science Applications International
Tadahiko Okumura	Shimizu Construction Company
Thomas O. Paine	Consultant
William L. Quaide	NASA Headquarters
Namika Raby	University of California, San Diego
Donald G. Rea	Jet Propulsion Laboratory
Gene Roddenberry	Writer
Harrison H. "Jack" Schmitt	Consultant
Richard Schubert	NASA Headquarters
Elie Shneour	Biosystems Associates, Ltd.
Martin Spence	Shimizu Construction Company
James B. Stephens	Jet Propulsion Laboratory
Pat Sumi	San Diego Unified School District
Robert Waldron	Rockwell International
Simon P. Worden	Department of Defense
William Wright	Defense Advanced Research Projects Agency

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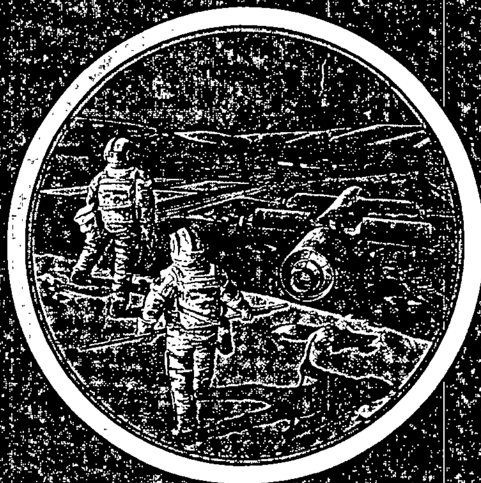
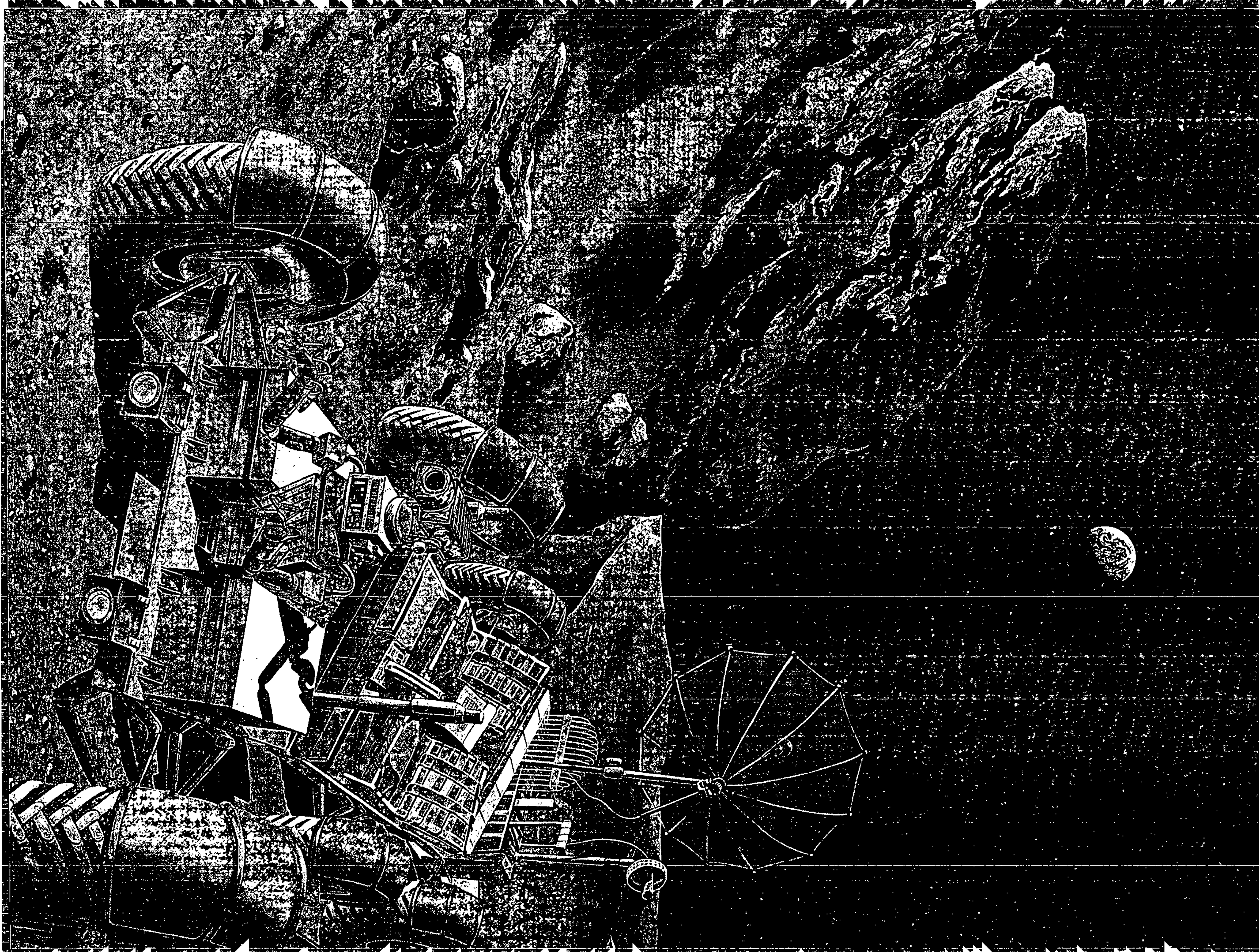
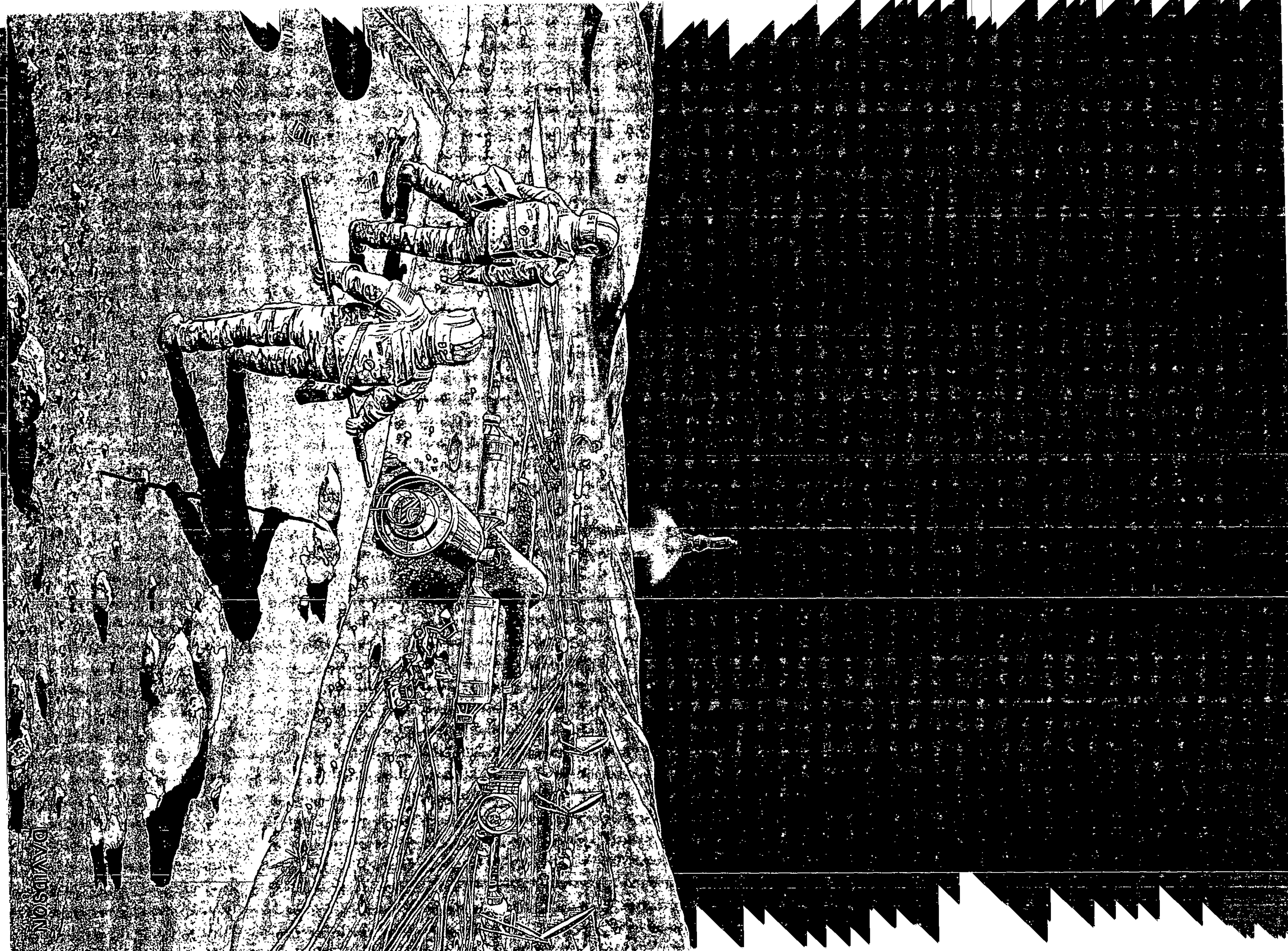
SPACE RESOURCES



Energy, Power, and Transport

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Frontispiece

Advanced Lunar Base

In this panorama of an advanced lunar base, the main habitation modules in the background to the right are shown being covered by lunar soil for radiation protection. The modules on the far right are reactors in which lunar soil is being processed to provide oxygen. Each reactor is heated by a solar mirror. The vehicle near them is collecting liquid oxygen from the reactor complex and will transport it to the launch pad in the background, where a tanker is just lifting off. The mining pits are shown just behind the foreground figure on the left. The geologists in the foreground are looking for richer ores to mine.

Artist: Dennis Davidson

Space Resources

Energy, Power, and Transport

Editors

Mary Fae McKay, David S. McKay, and Michael B. Duke

Lyndon B. Johnson Space Center
Houston, Texas

1992

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Preface

Space resources must be used to support life on the Moon and exploration of Mars. Just as the pioneers applied the tools they brought with them to resources they found along the way rather than trying to haul all their needs over a long supply line, so too must space travelers apply their high technology tools to local resources.

The pioneers refilled their water barrels at each river they forded; moonbase inhabitants may use chemical reactors to combine hydrogen brought from Earth with oxygen found in lunar soil to make their water. The pioneers sought temporary shelter under trees or in the lee of a cliff and built sod houses as their first homes on the new land; settlers of the Moon may seek out lava tubes for their shelter or cover space station modules with lunar regolith for radiation protection. The pioneers moved further west from their first settlements, using wagons they had built from local wood and pack animals they had raised; space explorers may use propellant made at a lunar base to take them on to Mars.

The concept for this report was developed at a NASA-sponsored summer study in 1984. The program was held on the Scripps campus of the University of California at San Diego (UCSD), under the auspices of the American Society for Engineering Education (ASEE). It was jointly managed by the California Space Institute and the Lyndon B. Johnson Space Center, under the direction of the Office of Aeronautics and Space Technology (OAST) at NASA Headquarters. The study participants (listed in the addendum) included a group of 18 university teachers and researchers (faculty fellows) who were present for the entire 10-week period and a larger group of attendees from universities, Government, and industry who came for a series of four 1-week workshops.

The organization of this report follows that of the summer study. *Space Resources* consists of a brief overview and four detailed technical volumes: (1) Scenarios; (2) Energy, Power, and Transport; (3) Materials; (4) Social Concerns. Although many of the included papers got their impetus from workshop discussions, most have been written since then, thus allowing the authors to base new applications on established information and tested technology. All these papers have been updated to include the authors' current work.

This volume—Energy, Power, and Transport—covers a number of technical and policy issues concerning the energy and power to carry out advanced space missions and the means of transportation to get to the sites of those missions. Discussed in the first half of this volume are the technologies which might be used to provide power and a variety of ways to convert power from one form to another, store it, move it wherever it is needed, and use it. In the second half of this volume are discussed various kinds of transportation including both interplanetary systems and surface systems.

This is certainly not the first report to urge the utilization of space resources in the development of space activities. In fact, *Space Resources* may be seen as the third of a trilogy of NASA Special Publications reporting such ideas arising from similar studies. It has been preceded by *Space Settlements: A Design Study* (NASA SP-413) and *Space Resources and Space Settlements* (NASA SP-428).

And other, contemporaneous reports have responded to the same themes. The National Commission on Space, led by Thomas Paine, in *Pioneering the Space Frontier*, and the NASA task force led by astronaut Sally Ride, in *Leadership and America's Future in Space*, also emphasize expansion of the space infrastructure; more detailed exploration of the Moon, Mars, and asteroids; an early start on the development of the technology necessary for using space resources; and systematic development of the skills necessary for long-term human presence in space.

Our report does not represent any Government-authorized view or official NASA policy. NASA's official response to these challenging opportunities must be found in the reports of its Office of Exploration, which was established in 1987. That office's report, released in November 1989, of a 90-day study of possible plans for human exploration of the Moon and Mars is NASA's response to the new initiative proposed by President Bush on July 20, 1989, the 20th anniversary of the Apollo 11 landing on the Moon: "First, for the coming decade, for the 1990s, Space Station *Freedom*, our critical next step in all our space endeavors. And next, for the new century, back to the Moon, back to the future, and this time, back to stay. And then a journey into tomorrow, a journey to another planet, a manned mission to Mars." This report, *Space Resources*, offers substantiation for NASA's bid to carry out that new initiative.

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ENERGY AND POWER: Introduction

Rocco Fazzolare

This workshop was directed to identify the energy and power needed to support activities in space, beyond the NASA Space Station Program, up to 2010.

Solar and nuclear heat sources are the basis of the production of energy in space. In this section we address stationary systems on a space platform and on the surface of a planetary body. Energy sources, conversion technology, heat rejection, and the delivery of power to the user—important elements that must be considered in system design—may vary according to system use.

In this report we define the power and energy requirements of future space activity with and without the utilization of resources from space, examine existing technologies for delivering the power, and arrive at some general conclusions as to the technology research and development needed to make possible the programs envisaged.

The first scenario, shown in figure 1, assumes the development of a space network with all materials and resources shipped from the Earth. A balanced development is assumed, with slight increases over the current

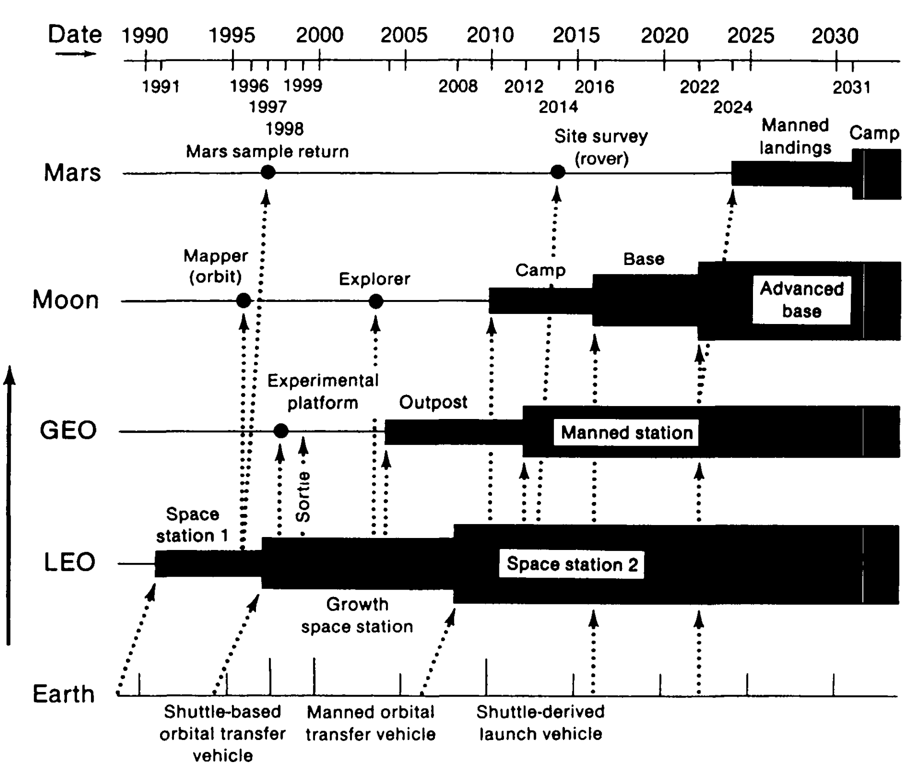


Figure 1

Baseline Scenario

If NASA continues its business as usual without a major increase in its budget and without using nonterrestrial resources as it expands into space, this is the development that might be expected in the next 25 to 50 years. The plan shows an orderly progression in manned missions from the initial space station in low Earth orbit (LEO) expected in the 1990s, through an outpost and an eventual space station in geosynchronous Earth orbit (GEO) (from 2004 to 2012), to a small lunar base in 2016, and eventually to a Mars landing in 2024. Unmanned precursor missions would include an experiment platform in GEO, lunar mapping and exploration by robot, a Mars sample return, and an automated site survey on Mars. This plan can be used as a baseline scenario against which other, more ambitious plans can be compared.

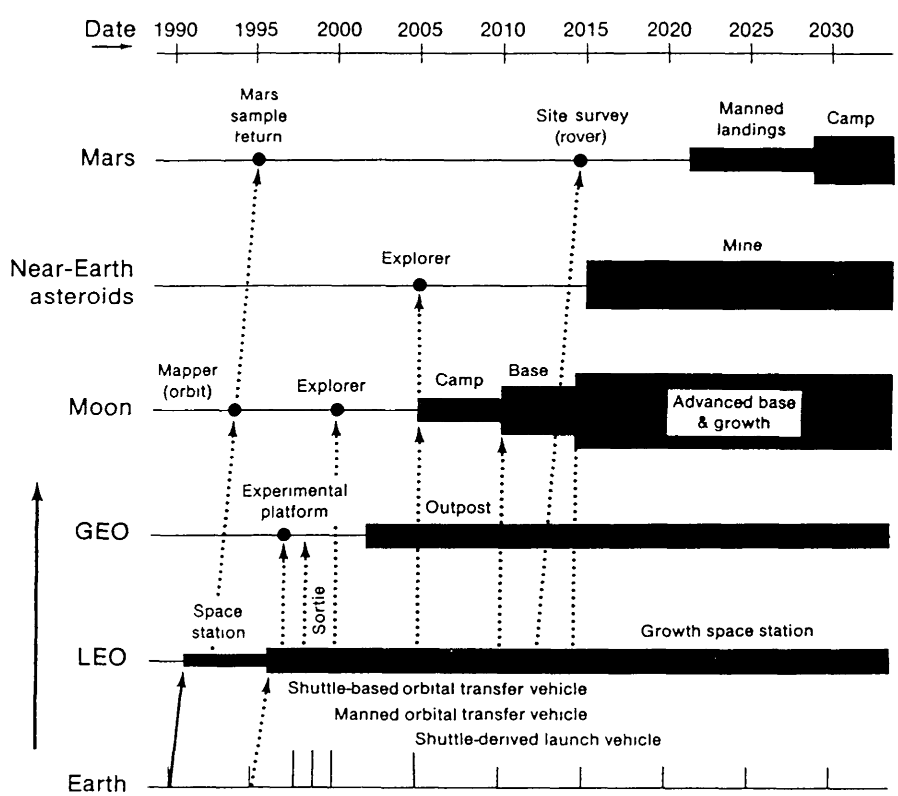
Figure 2

Scenario for Space Resource Utilization

Space resource utilization, a feature lacking in the baseline plan, is emphasized in this plan for space activities in the same 1990-2035 timeframe. As in the baseline scenario, a space station in low Earth orbit (LEO) is established in the early 1990s. This space station plays a major role in staging advanced missions to the Moon, beginning about 2005, and in exploring near-Earth asteroids, beginning about the same time. These exploration activities lead to the establishment of a lunar camp and base which produce oxygen and possibly hydrogen for rocket propellant. Automated missions to near-Earth asteroids begin mining these bodies by about 2015, producing water and metals which are returned to geosynchronous Earth orbit (GEO), LEO, lunar orbit, and the lunar surface. Oxygen, hydrogen, and metals derived from the Moon and the near-Earth asteroids are then used to fuel space operations in Earth-Moon space and to build additional space platforms and stations and lunar base facilities. These space resources are also used as fuel and materials for manned Mars missions beginning in 2021. This scenario might initially cost more than the baseline scenario because it takes large investments to put together the facilities necessary to extract and refine space resources. However, this plan has the potential to significantly lower the cost of space operations in the long run by providing from space much of the mass needed for space operations.

budget. The space station, which is already programmed, is used to support development in geosynchronous Earth orbit (GEO), manned exploration of the Moon, and unmanned exploration of the solar system. Eventually, beyond 2010, a lunar base and manned exploration of Mars are undertaken.

In the second scenario (fig. 2), nonterrestrial resource utilization is assumed to be a goal. The paths are similar to those shown in the baseline scenario, but there is a heavier emphasis on movement to the Moon and establishment of a manned base there. Lunar materials are processed to get oxygen to support the transportation system in low Earth orbit (LEO). Selective mining of near-Earth asteroids is considered feasible. The lunar base and the production there enhance the move toward manned Mars exploration.



This section of the report includes two subsections describing "Power System Requirements" in space and the "Technologies" needed to fulfill these requirements. In the first paper, Ed Conway estimates the requirements for power to support the two scenarios, focusing on the requirements for activities at these nodes: low Earth orbit, geosynchronous Earth orbit, the Moon, Mars, and asteroids. He identifies the appropriate technologies for each activity. Henry Brandhorst then describes the solar-energy-related technologies that may be applicable, focusing on photovoltaics and solar dynamics.

Dave Buden explores the development of nuclear power supplies for space applications. Abe Hertzberg addresses the problem of thermal management in space and describes a liquid droplet radiator. Conway discusses laser transmission of power, which if developed can influence the evolution of larger, more centralized, space power-generation stations. Finally, Brandhorst discusses the implications of space power development for the missions to be carried out within the two broad scenarios; he advances the recommendations of the workshop in this area.

Power System Requirements

Edmund J. Conway

We estimated the electrical power required for each mission in the baseline model (fig. 1) and in the alternative model (fig. 2), according to the specific energy-using activities and operations shown. We then identified appropriate technologies to meet these power requirements, using such criteria as, Can the technology fully meet the requirement? and, Can the technology be ready at least 5 years before the mission? In some cases, there were competing technologies for the same mission.

Low Earth Orbit (LEO)

The initial space station, scheduled for the mid-1990s, will have 75-300 kW (electric) of continuous bus power. Mid- to late 1980s' solar photovoltaic technology is the only proven power-generating option available. However, solar photovoltaic systems require large arrays and consequently produce substantial drag. To provide power above the 75-kW level, two technologies could compete: solar dynamic (solar thermal with Stirling-, Brayton- or Rankine-cycle conversion) and nuclear thermal (with thermoelectric, thermionic, or dynamic conversion). Both technologies are now in developmental phases.

A second-generation space station appears in the baseline model at 2008. It would be needed for large-scale space processing of terrestrial materials. Space Station 2 would require from one to tens of megawatts. Such a mission would provide a major pull on the power-generating technologies. The current choice would appear to be some type of nuclear power system.

For power requirements above 1 megawatt, serious technology issues also arise in electrical power management (high voltage and current) and thermal management (how to dispose of 1 MW of low-temperature heat). Electrical power management would require both a new philosophy and some new technology. Thermal management would require such new technology as a large liquid droplet radiator.

Geosynchronous Earth Orbit (GEO)

By the late 1990s, a geosynchronous experimental science platform would require up to 10 kW. This requirement could be met by solar photovoltaic power. Advanced lightweight power generation and storage systems might be required if the present limitations on payload mass to GEO have not been eased significantly. Such systems, including those with gallium arsenide solar cells and high specific-power chemical storage, are in the research stage now.

By 2004, a GEO shack or temporarily inhabited repair shop on the platform will allow for human-tended and interchangeable experiments. To operate in the repair shop, the human tenders would need additional power, on the order of 10 kW. This power could be supplied by the visiting spacecraft. Solar photovoltaic technology, similar to that already mentioned for the platform, could be used.

A manned GEO station could be required beyond 2010. The power level anticipated and the enabling technology are similar to those of the LEO growth space station. Thus, geosynchronous Earth orbit provides no new power challenges.

Moon

An orbital lunar mapper in the mid- to late 1990s has only small power requirements, which can be met by 1980s' technology. An unmanned surface explorer (compare fig. 3), beginning in 2004, would require only a few (2-5) kilowatts continuously, for movement, surface coring, analysis, and telemetry. A radioisotope generator (compare fig. 4) with dynamic conversion is the technology of choice.

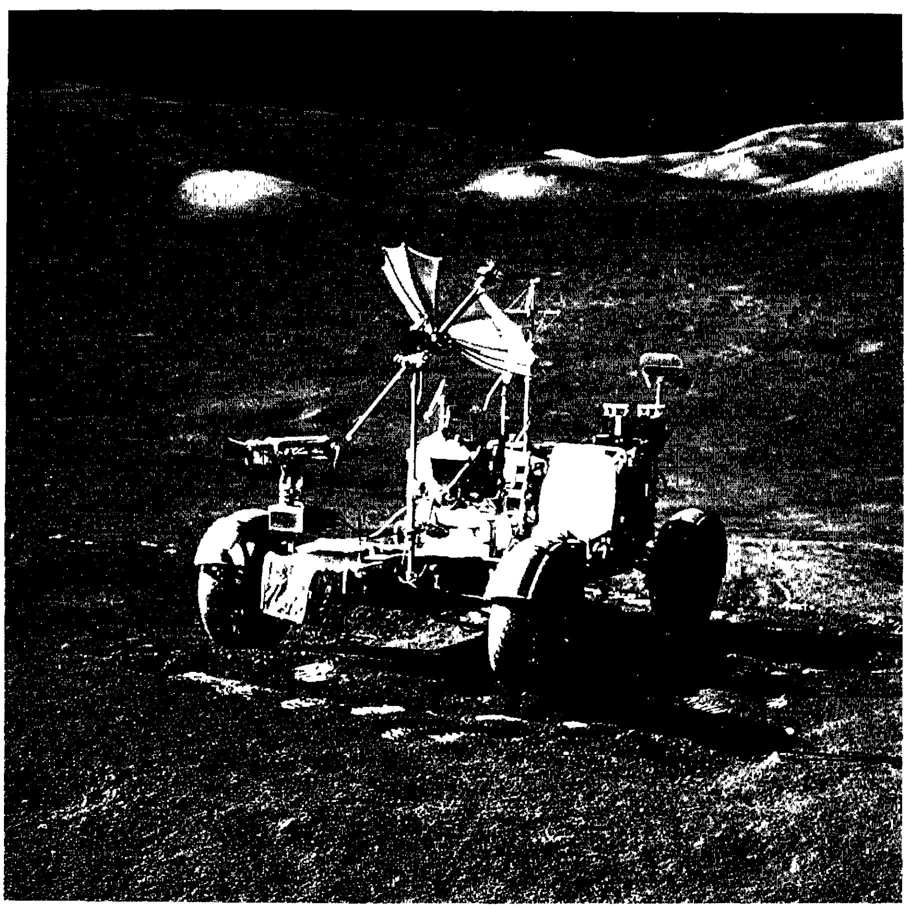


Figure 3

Lunar Rover Used on the Apollo 17 Mission

An automated unmanned version of this rover might be useful on future lunar missions. While seemingly simple, this Apollo Rover contained many of the elements necessary for a completely unmanned rover—a sophisticated redundant power system, power steering, automatic thermal control, a dust control system, and a self-contained navigation system which kept track of the location of the Rover at all times

The Apollo 17 Rover, using two 36-volt silver-zinc batteries rated at 121 amp-hours each, traveled a maximum distance from the Lunar Module (LM) of 7.6 km. For long unmanned traverses, battery power would probably not be practical because of the relatively low energy density of batteries.

A completely automated rover with an artificial intelligence (AI) system or a teleoperated rover are two possible versions for future applications.

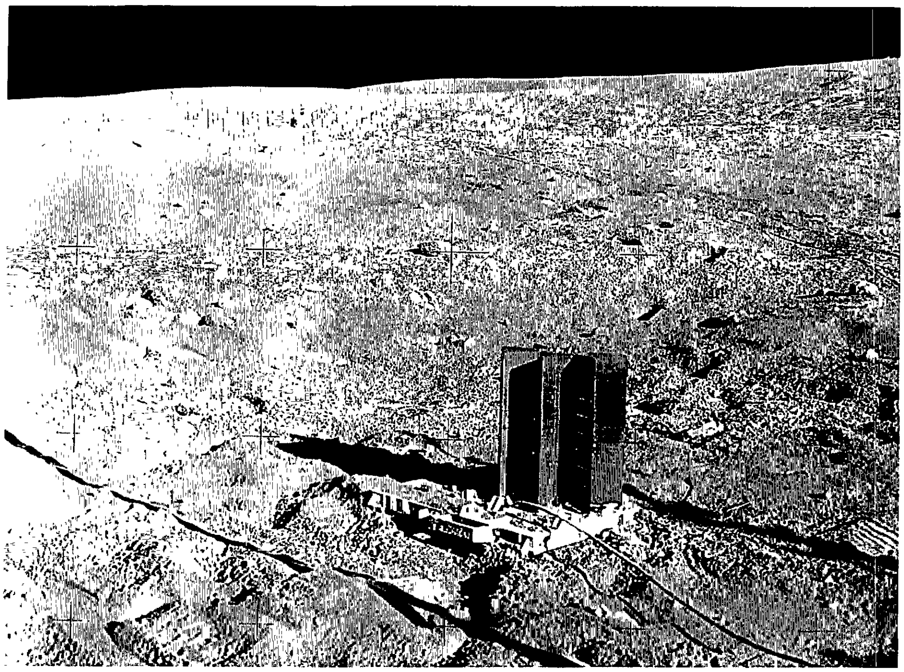
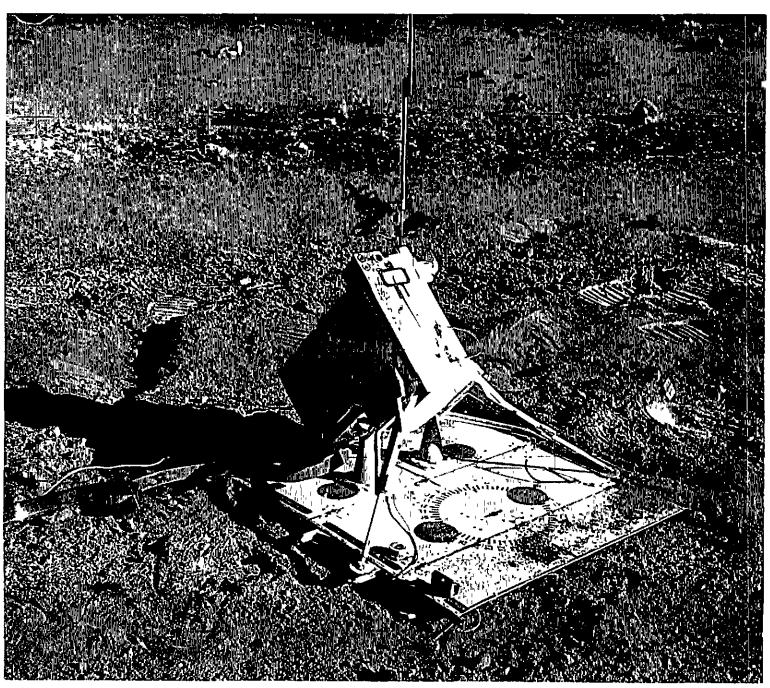


Figure 4

a. Radioisotope Thermoelectric Generator

This radioisotope thermoelectric generator (RTG) was the power source for the Apollo lunar surface experiments package (ALSEP) on the Apollo 16 mission. This power generator contains fins for radiating away excess heat. On this mission it powered an active seismic experiment (see accompanying fig.), a passive seismic experiment, a surface magnetometer, a heat flow experiment, and the central control and communications station.



b. Mortar Firing Assembly for the Active Seismic Experiment

This assembly in the ALSEP was designed to fire four grenades out to a maximum distance of 1.5 km. The grenades were designed to explode on impact, generating a seismic signal which would be picked up by a string of three geophones. On the actual mission, only three of the grenades were used and the maximum distance traveled was about 900 m. This experiment determined the thickness and seismic velocity of the near-surface structure at the Apollo 16 site.

By 2010, a lunar camp, to be inhabited only during the 2 weeks of lunar day, would initially require 25 kW, supplied by a solar photovoltaic system. This initial power level could be augmented during future visits using similar or improved photovoltaic technology. Or the lunar camp's power system could grow, in the same manner as that of the space station, to include solar dynamic or nuclear supplies. The initial power level is suitable for crew life support, lunar science, and light work, but it does not provide the storable energy for heat and life support during the lunar night. For full-time habitation, the camp and later the base would rely on nuclear power supplying a few hundred kilowatts. (See the analogy in figure 5.) High power requirements away from the base for transportation or mining could be supplied by a separate source or by transmission. Point-to-point beamed transmission along the surface or between surface and space is possible.

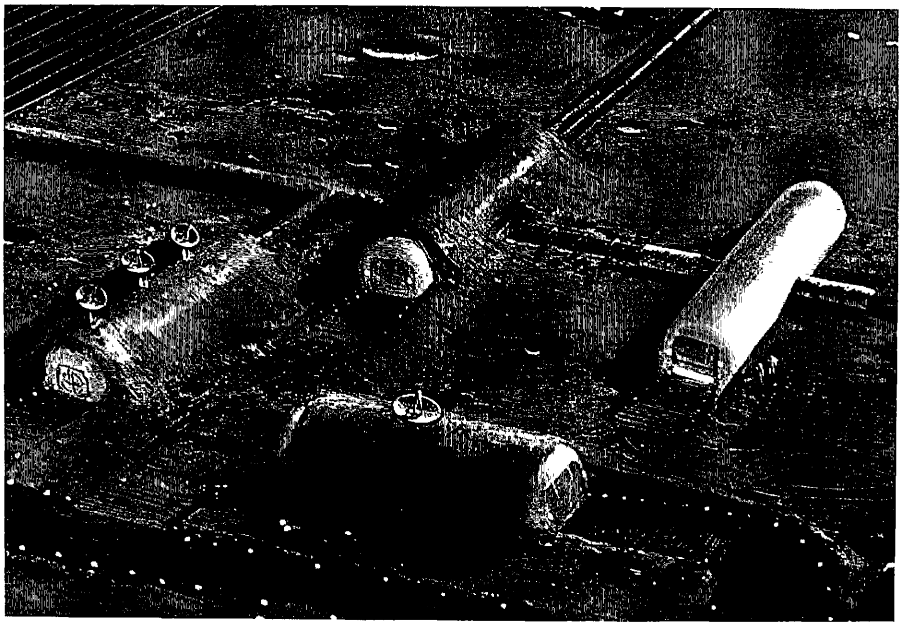


Figure 5

a. Spartan Lunar Base

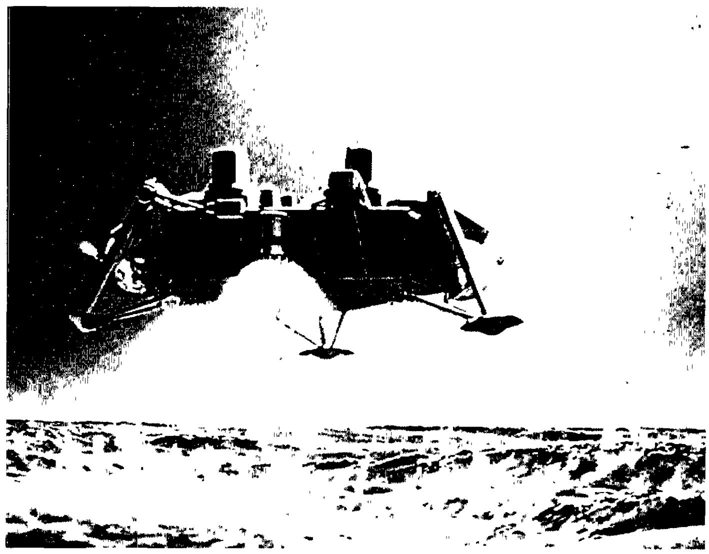
The early lunar base may consist of several modules similar to habitation and laboratory modules for the space station, which can be transported to the lunar surface and covered with lunar regolith for radiation protection. In many ways this early base would be like the American Station at the South Pole, which is probably the closest thing we have to a base on another planet.

b. South Pole Station

The South Pole station is continuously occupied, but crewmembers arrive or depart only during the summer season While the occupants can venture outside with protective clothing ("space suits") during the winter, they are mostly dependent on the shelter provided by the geodesic dome and the buildings within the dome, much as they would be at a Moon or Mars base.

Analogous to the Antarctic winter is the lunar night. More power would be required for heating and lighting in both cases. Even more important on the Moon, solar power would not be available at night unless massive storage was provided. Continuous occupation of a lunar base would probably rely on nuclear power.

Photo: Michael E. Zolensky



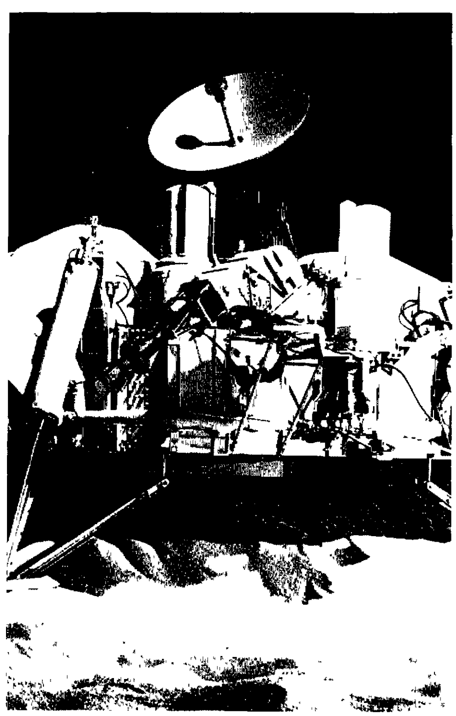


Figure 6

Unmanned Mars Lander

In one concept (above), an unmanned Mars lander is bringing in a scientific package and ascent system while a small rover is parachuted to the surface in the distance. The rover could then travel to the lander in the foreground, collecting samples along the way. The rover would deliver the samples to the ascent system, which would take them into martian orbit and start them on their way back to Earth.

Much of the basic technology for such a mission was developed and successfully tested by the Viking lander (right). The Soviet Luna missions successfully returned lunar samples to Earth in the early 1970s. Electrical power requirements for such missions are quite small compared to those for any manned mission.

Mars

The baseline and alternative scenarios identify only one mission to Mars by 2010, the Mars sample return. This mission would require only very limited power, which could be provided by current technology—a radioisotope thermoelectric generator. The later Mars site survey rover would have power requirements similar to the lunar surface explorer (2-5 kW) and, like it, would rely on a radioisotope generator with a dynamic converter. (See figure 6.)

Asteroids

The alternative model (fig. 2) includes unmanned exploration of an asteroid beginning in 2005. This involves activities and power requirements similar to those for the earlier lunar surface explorer and could be handled by a similar system.

Mining (not included in the scenario) would require power on the order of 10 MW. A nuclear reactor power system developed for general application to industrial processing in space would be utilized. See figure 7 for a medium-range application on one of the asteroid-like moons of Mars.

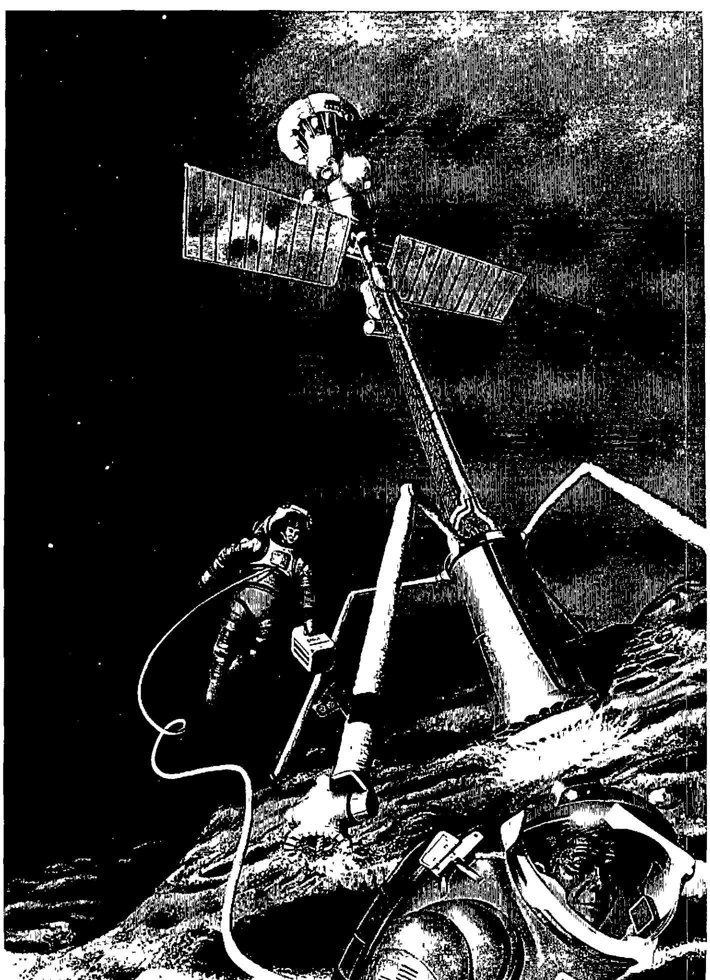


Figure 7

Phobos Deimos Hot Drill

The Phobos/Deimos (PhD) "hot drill" is designed to melt its way into the regolith of one or the other of these satellites, liberating volatiles (mainly water) as it goes. Water could be trapped and electrolyzed into hydrogen and oxygen for use as propellants to refuel the martian lander or the Earth-Mars vehicle.

Artist Pat Rawlings

Technologies

Henry W. Brandhorst, Jr.

Photovoltaic Technology

Solar cells have been the workhorse of the space program for nearly all missions lasting longer than a few weeks. Several components are needed for reliable power production from solar cells. Solar cells must be interconnected to provide the requisite voltage and current levels. This matrix must be supported on a substrate such as aluminum honeycomb or a plastic like Kapton. The individual cells also must be covered to provide protection against the electrons and protons found in the Earth's radiation belt and in ejecta from the Sun. Finally, some sort of deployment or erection mechanism must be supplied to extend the solar array from the spacecraft. The mass of the system is made up of these components, along with the power management and distribution system and the storage system needed to provide power during the dark phase.

Currently silicon solar cells are the prime power source for satellite use. Maximum individual efficiency is about 14 percent in volume production of 200-1000 kW. Cell size ranges from 2 by 4 cm to 8 by 8 cm, and the cells cost about $100 per watt. When these cells are mounted in an array, the overall power produced is about 100 W/m^2. The largest solar array built to date was that for Skylab and the Apollo Telescope Mount (ATM), with a total power of roughly 20 kW (fig. 8). In low Earth orbit, this array should have produced a bus power of 7.5 kW. (Charging efficiency and the cycle of a 60-minute day followed by a 40-minute night reduces the average power.) Because one-fourth of the array was lost during launch, the total power on orbit was reduced accordingly. The specific power (watts of electricity produced per kilogram of array mass) of these rigid panels was 10-15 W/kg. When combined with the nickel-cadmium electrochemical energy storage system, the total solar power system had a specific power of approximately 6 W/kg. Silicon arrays also powered the first Apollo lunar surface experiments package (ALSEP) on the Moon.

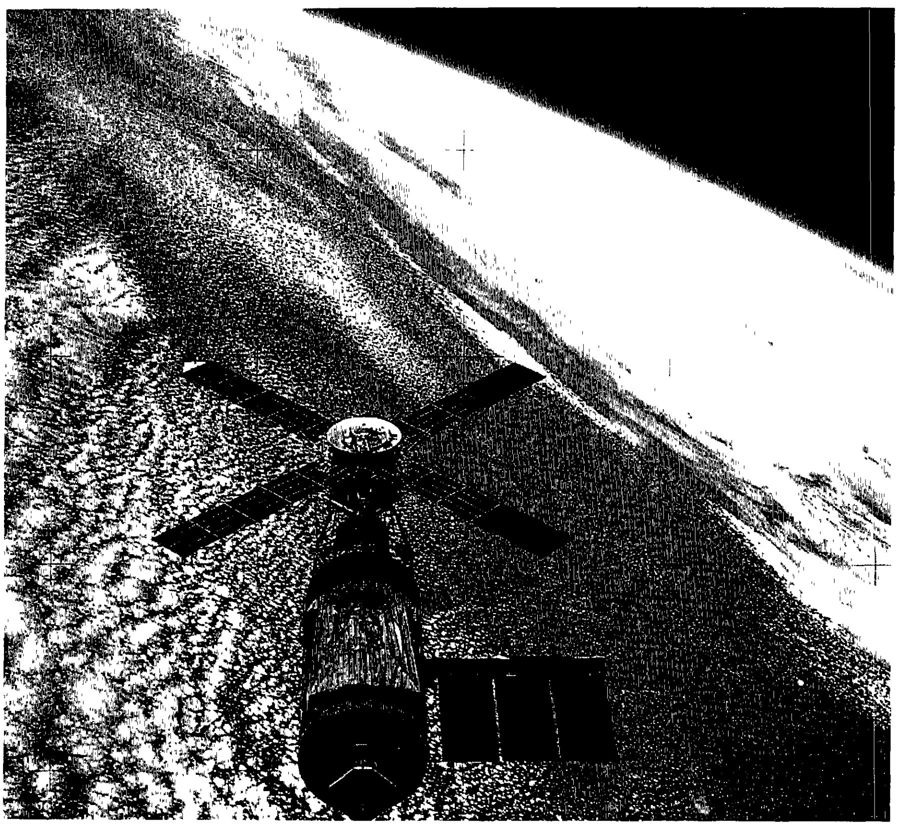


Figure 8

Skylab Solar Power

This photo shows the Skylab space station cluster with its large solar arrays. This is the largest solar power system yet put in space. These panels had a power production capacity of 10-15 W/kg and a total maximum power rating of about 20 kW, but loss of the left array during launch reduced the total power by about one fourth.

Present rigid solar arrays, typified by the Tracking and Data Relay Satellite (TDRS) in geosynchronous orbit, have a specific power of 25 W/kg and a cost of about $750/W. Total power is 2.7 kW, which is typical of a communications satellite (see fig. 9). A lightweight silicon solar array with a Kapton substrate was tested on the Shuttle in 1984. This array had a specific power of 66 W/kg and was sized to produce 12 kW of power, although only enough cells to produce about 200 W were actually put in place. This array was 102 feet long and 13 feet wide.

Advances expected in the near future include the lightweight, 50-micrometer-thick silicon solar cell blanket. These cells are one-fourth the thickness of conventional cells. The specific power goal for these lightweight arrays is 300 W/kg. These cells and arrays are aimed at applications where mass is critical, such as uses in geosynchronous orbit and exploration of the Moon and the solar system. These cells are also more resistant to the damaging effects of space radiation than thicker silicon solar cells and thus promise longer life in such orbits.

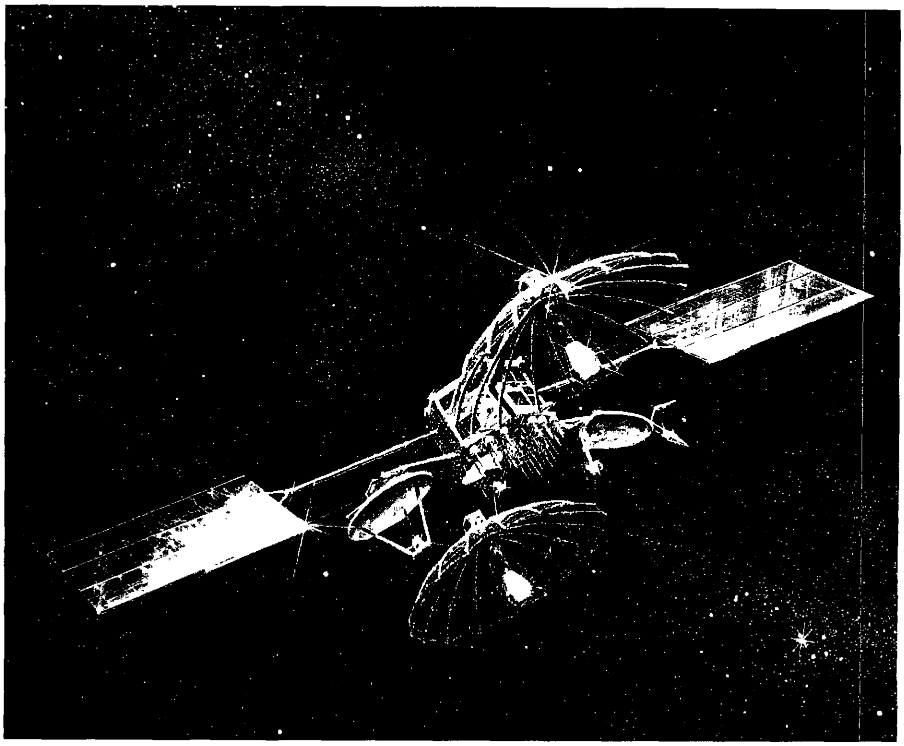


Figure 9

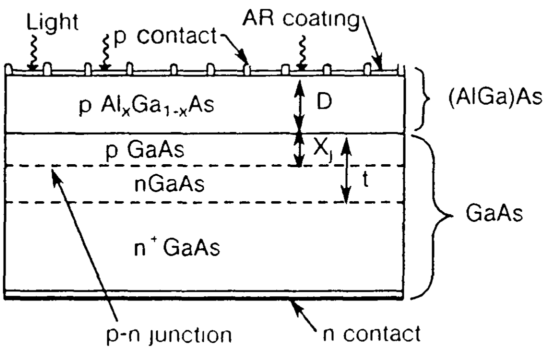
Tracking and Data Relay Satellite (TDRS)

A constellation of three Tracking and Data Relay Satellites is being placed into geosynchronous Earth orbit (GEO) to enable satellites in low Earth orbit (LEO) to be in nearly constant (80% of the time) communication with their ground stations. Signals to and from the LEO satellites will be relayed through the TDRS and a single ground station at White Sands, New Mexico.

These large satellites (2200 kilograms) are powered by solar arrays spanning over 50 feet. The solar arrays provide more than 1700 watts of electrical power and have a projected lifetime of over 10 years. During the short time that the satellite is in the shadow of the Earth, full power is supplied by nickel-cadmium batteries.

Artist: P. J. Weisgerber

Gallium arsenide (GaAs) solar cells (fig. 10) are being developed as an alternative to silicon cells. These cells have a higher efficiency (17-21%) than silicon cells and are less sensitive to heat. Present production capability is about 10 kW/year. Current costs of GaAs cell arrays are expected to be about \$1500/W, with a cost goal of \$500/W. Array technology is expected to be similar to silicon cell technology. Gallium arsenide cells were used on the Moon to power the U.S.S.R. lunokhod rover (fig. 11). Flight of GaAs arrays is expected in the late 1980s.



p contact: Au-Zn-Ag
n contact: Au-Ge-Ni-Ag
AR coating: Ta_2O_x
p $Al_xGa_{1-x}As$: x = 0.87
Cell size = 2 cm x 2 cm

$D < 0.5\ \mu m$
$X_j \leq 0.5\ \mu m$
$t > 10\ \mu m$

Figure 10

Structure of Aluminum Gallium Arsenide/Gallium Arsenide Solar Cell

In this advanced version of a gallium arsenide (GaAs) solar cell, the aluminum gallium arsenide [(AlGa)As] layer nearest the top (p contact) increases the efficiency of the cell compared to that of the simple GaAs cell Gallium arsenide cells can have higher efficiencies than silicon cells, and advanced design GaAs cells may be able to achieve efficiencies of 30 percent.

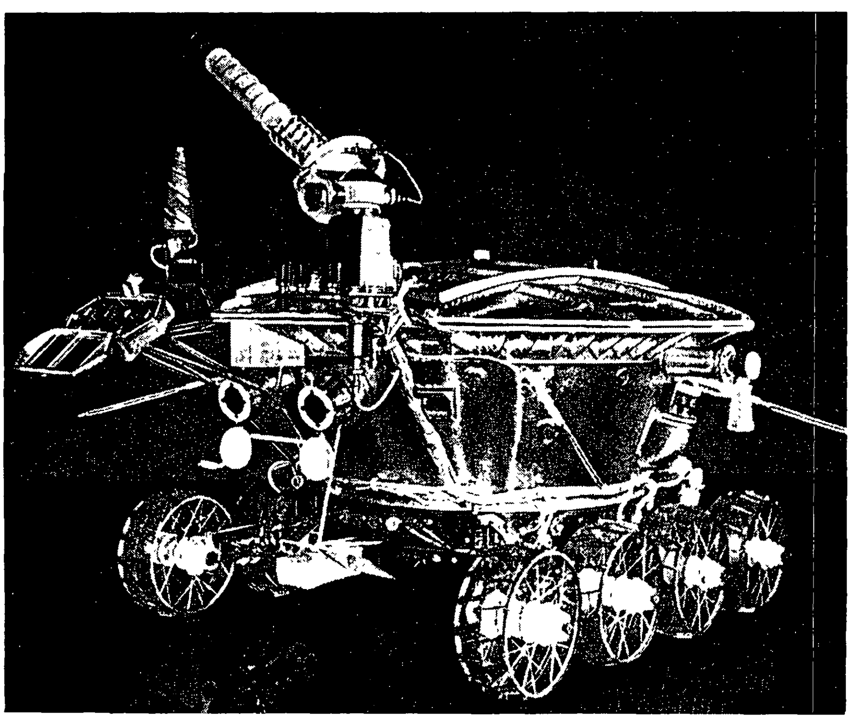


Figure 11

Lunokhod Rover

The Soviet lunokhods were unmanned rovers which traveled from 10 km (Lunokhod 1) to nearly 40 km (Lunokhod 2) across the lunar surface transmitting images and a variety of scientific data back to Earth. These lunokhod rovers were powered by GaAs solar cells.

An emerging technology aimed at achieving lower GaAs array cost is to use sunlight concentration. Miniature Cassegrainian concentrator elements 2 inches in diameter and 1/2 inch thick are being developed (fig. 12). These devices concentrate sunlight about 100 times and illuminate 5- by 5-mm GaAs cells. Because of the small size and novel design, cell operating temperature is about 85°C, not much higher than the 60°C temperature at which a conventional silicon cell array in low Earth orbit operates. The cost of these emerging arrays is expected to be roughly one-third the cost of silicon arrays or about $150-300/W. Alternative optical concepts, such as reflective or refractive Fresnel lenses, are also under study. Gallium arsenide arrays are expected to produce 160-180 W/m^2 at a specific power of 25-40 W/kg.

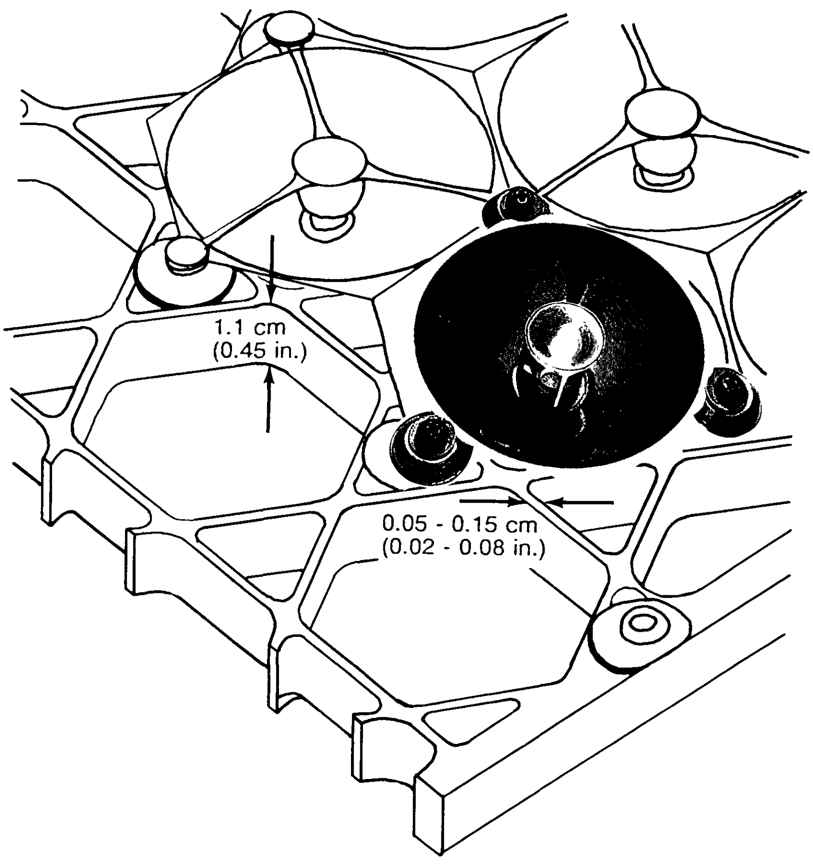


Figure 12

Miniature Cassegrainian Solar Concentrator

Small Cassegrainian optics concentrators, only about 5 cm in diameter and 1.2 cm thick, have been designed to concentrate sunlight on tiny (only 5 by 5 mm) gallium arsenide solar cells. This design provides a basic concentration factor approaching 100 to 1.

They are also more radiation-resistant than silicon arrays, both inherently and because of the shielding provided by the metallic concentrator element. Furthermore, cover-glass shielding can be provided at little increase in mass. This radiation resistance permits operation in heavy radiation orbits within the Van Allen belt (fig. 13) and opens the door to a solar-electric-propelled orbital transfer vehicle (OTV). This technology is being explored for space station applications. It appears feasible to build such arrays in the 500-kW range (up to 1 MW with advanced higher efficiency cascade cells). Such power levels enable short trip times from LEO to GEO (several trips per month), and this technology appears suitable for lunar base operation.

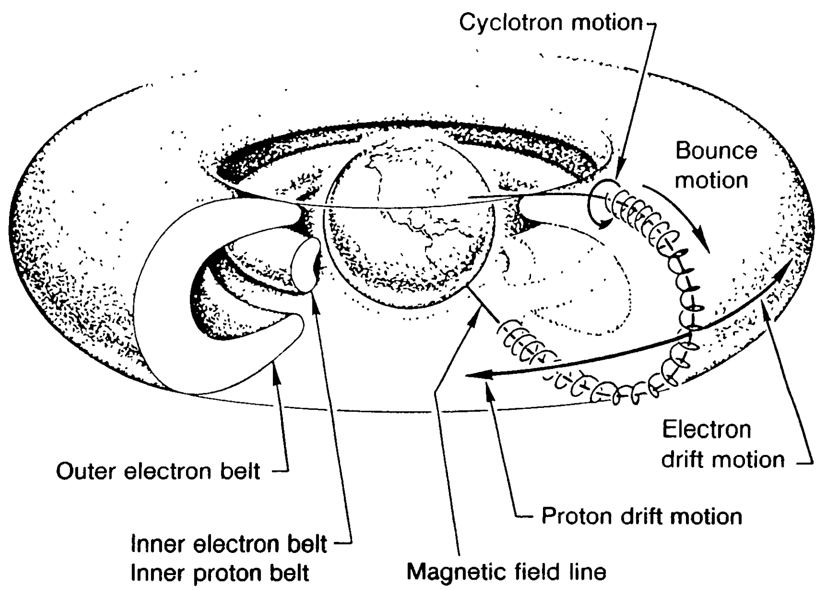


Figure 13

Van Allen Radiation Belt

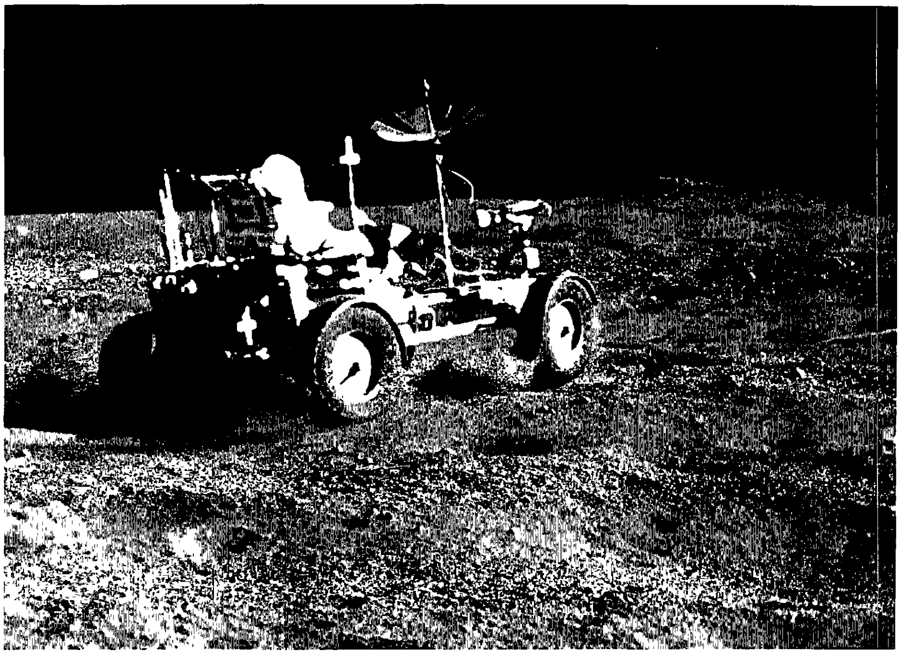
Named for its discoverer, James A. Van Allen, the Van Allen belt is a zone of high-intensity particulate radiation surrounding the Earth beginning at altitudes of approximately 1000 km. The radiation of the Van Allen belt is composed of protons and electrons temporarily trapped in the Earth's magnetic field. The intensity of radiation varies with the distance from the Earth. Spacecraft and their occupants orbiting within this belt or passing through it must be protected against this radiation.

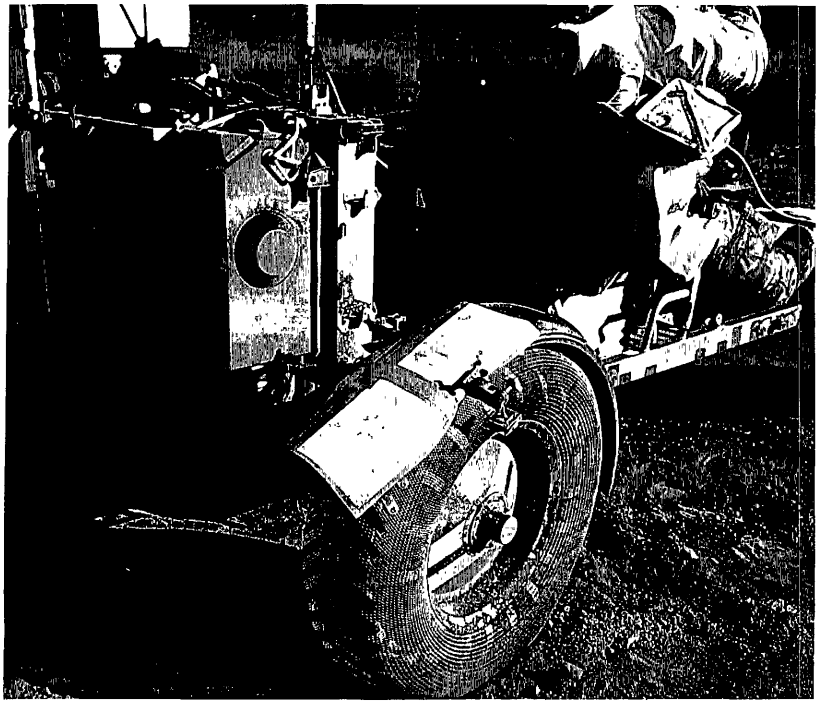
Ultralightweight GaAs cell technology has produced a cell only 6 micrometers thick with a 14-percent conversion efficiency and a specific power of 5 kW/kg. When coupled with lightweight array technology, such cells have applicability to GEO and lunar base operations.

An emerging cell technology is the cascade cell, made from combinations of elements from the third and fifth columns of the periodic table. Three junction cells arranged in tandem atop one another may be able to achieve 30-percent conversion efficiency at 100 times solar concentration and at 80°C. If development of these advanced cells is successful, very high power per unit area (approaching 300 W/m^2) and a specific power of 75 W/kg appear feasible. These technologies may become available about 1990.

Photovoltaic systems could be used for daytime operation on the lunar surface and for power at stations in GEO or lunar orbit. The specific characteristics required depend on the application. Solar arrays up to 300 kW with silicon planar or GaAs concentrator technology appear reasonable. Ultralightweight arrays based on silicon technology should be available by 1990, with GaAs technology following a few years later.

Operation on the lunar surface adds requirements. First, dust accumulation on cells or optical surfaces will degrade performance, and actual operating temperatures will be greater because of the nearby lunar surface. The dust and lunar environment may also affect the maximum array voltage as a result of arcing phenomena. Finally, arrays must be designed to accommodate the deep temperature cycling of the day-night cycle. The most likely use of solar arrays on the lunar surface will be to power daytime-only operations because the mass of known energy storage for the 2-week lunar night is large and makes the total system less attractive than nuclear power systems.





Lunar Dust

During the high-speed "Grand Prix" on the Apollo 16 mission, a large "rooster tail" of dust was thrown up behind the Rover (top), even though each wheel was equipped with a fender. During the first excursion on the Apollo 17 mission, part of the right rear fender was lost. Without the fender, the wheel threw up a big plume of dust which started to cover the Rover and the crew. This was such a hazard that further use of the Rover was in doubt. However, the astronauts rigged a makeshift fender (bottom) using a map, tape, and two clamps from the Lunar Module (LM), and this repair proved satisfactory for subsequent excursions. Thus, if it is not properly controlled, the dust thrown up by moving vehicles on the Moon could be a major contaminant of lunar equipment.

It has been suggested that lunar material could be mined for the production of photovoltaic devices (fig. 14). The production of high-capacity photovoltaics would be limited by the availability of materials and manufacturing capability in space; thus, it is not considered plausible by 2010. However, the use of lunar-derived systems for energy storage should be investigated.

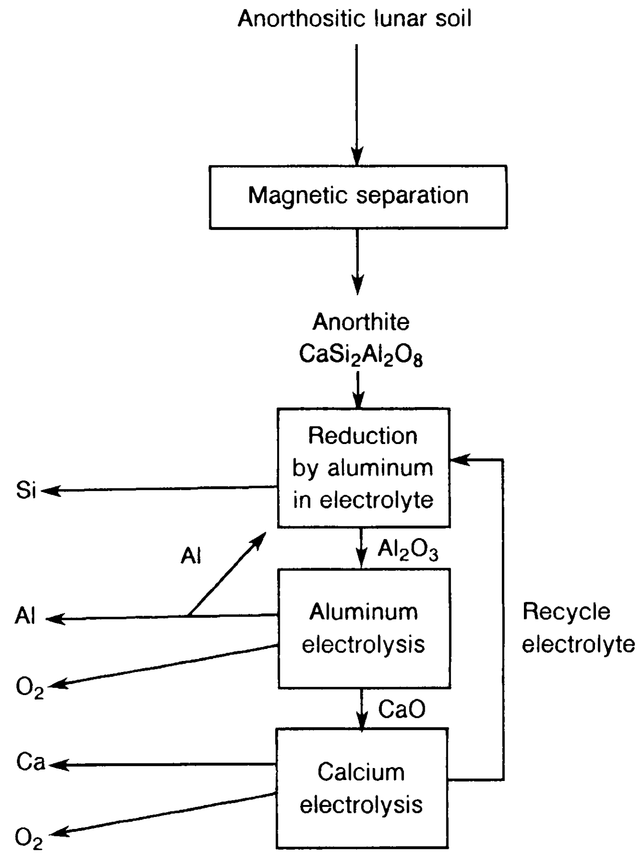


Figure 14

Production of Solar Cells From Lunar Material

Solar cells made from lunar silicon are a possibility. This block diagram shows a process developed by EMEC Consultants for the production of solar-cell-grade silicon from lunar soil. The process uses aluminum metal to reduce the plentiful silicon in the mineral anorthite, the most abundant mineral on the Moon. This silicon can potentially be purified and fabricated into solar cells.

In the process, aluminum metal becomes aluminum oxide, which is subsequently separated into aluminum and oxygen by electrolysis. Some of the aluminum is then recycled to produce more silicon, and some can be used for construction purposes. The oxygen can be liquefied and used for life support or for rocket propellant. Additional oxygen can be produced by electrolysis of the calcium oxide derived from the anorthite.

Solar Dynamic Technology

Solar dynamic systems consist of a mirror that focuses sunlight on a receiver (which may contain thermal storage) and a Carnot-cycle dynamic conversion system (with heat radiation). (See figure 15.) The most common conversion cycles studied are the Stirling (fig. 16), Rankine (fig. 17), and Brayton (fig. 18). All have cycle efficiencies in the 25- to 35-percent range. When research on these systems for space use was terminated in the early 1970s, a Brayton system had been tested for a total of 38 000 hours (about 5 years). Commercial low-temperature (750°F) organic Rankine systems have also operated for tens of thousands of hours. Development of Stirling cycles is proceeding under the SP-100 Program, and space station research may support Brayton and Rankine cycle work.

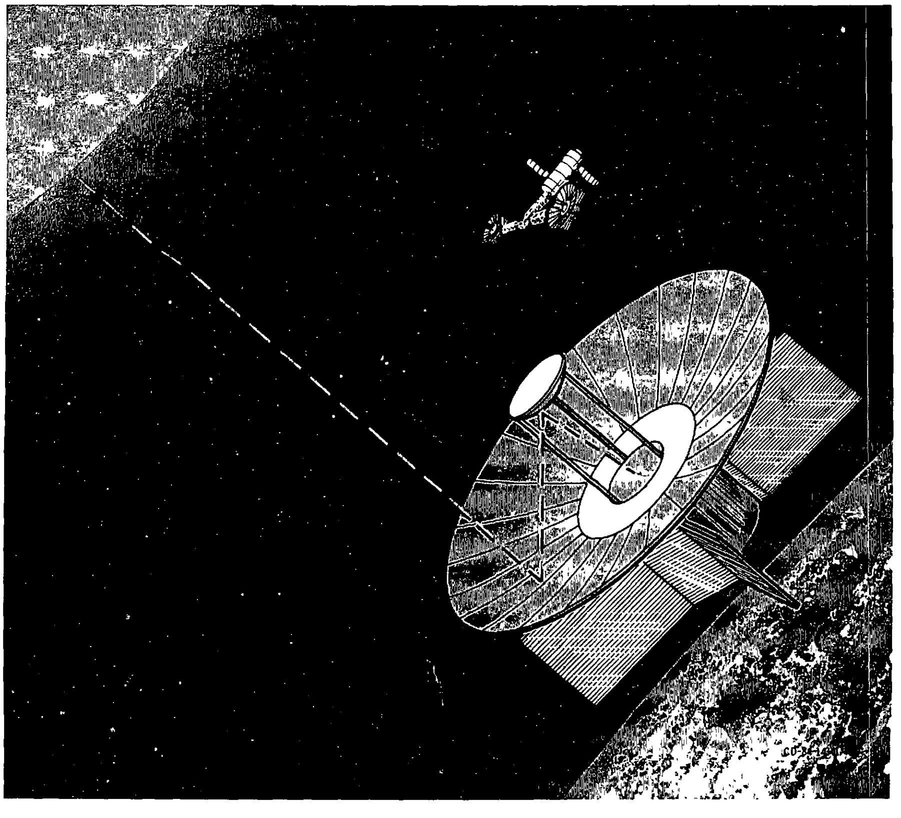


Figure 15

Solar Dynamic Power

Any system that uses solar energy to drive moving machinery which generates electricity is a solar dynamic system. Normally the solar energy is concentrated by mirrors to increase its intensity and create higher temperatures. Here, a Cassegrainian optics concentrator focuses energy on a heat engine.

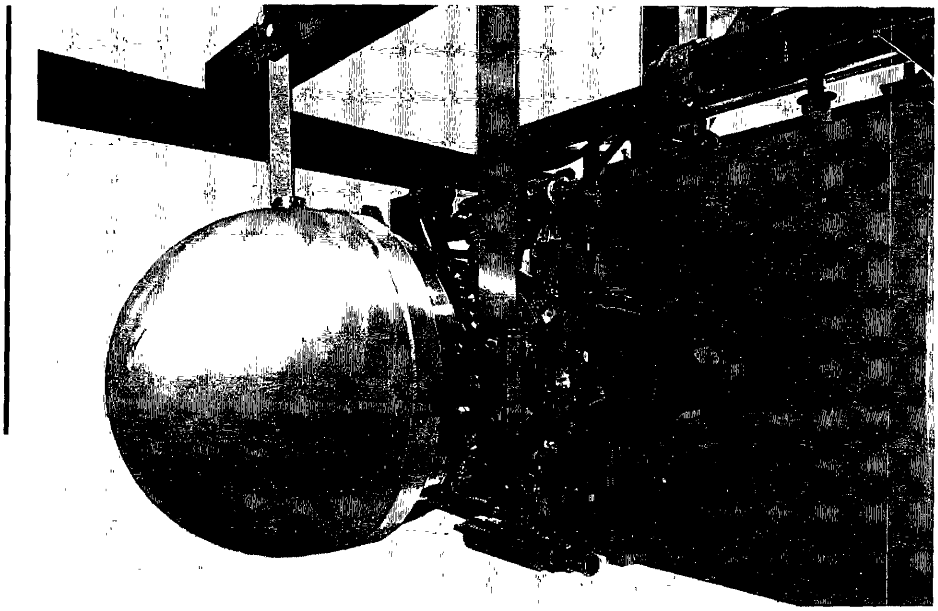
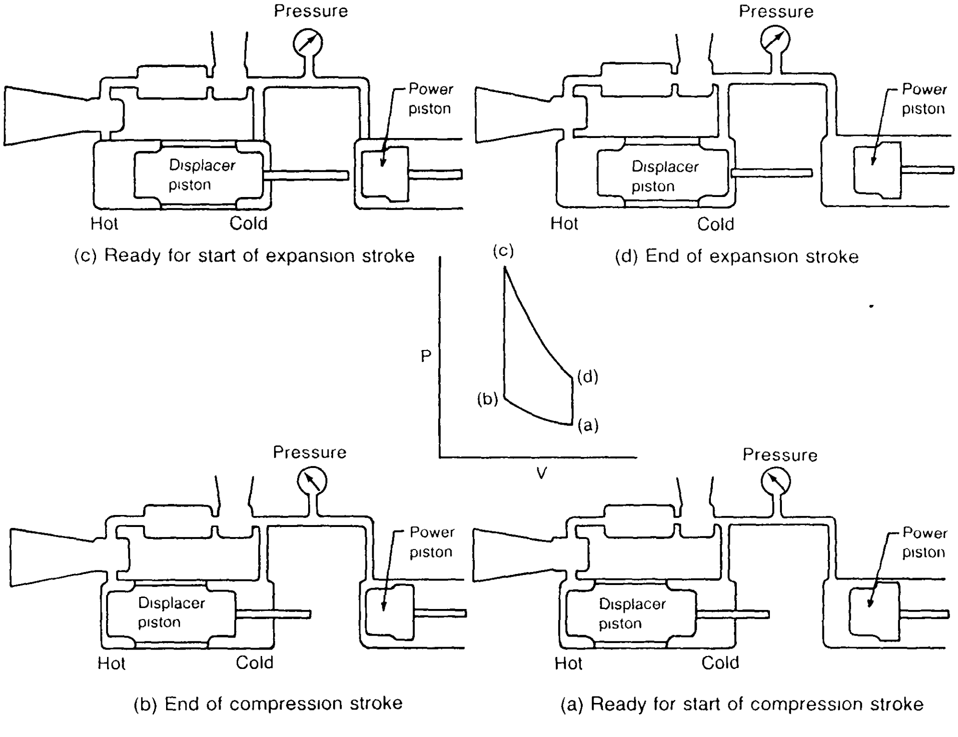


Figure 16

Stirling Cycle

In the Stirling engine, solar energy is used to heat a working gas and move a series of pistons which convert the heat energy into mechanical energy to drive an electric generator. Starting at (a), *the power piston is moved in its cylinder by the momentum of the turning electric generator. The piston compresses the gas and reduces its volume until* (b) *is reached. Then solar heat (from the left) causes the gas to expand and move the displacer piston* (c). *This heat expansion greatly increases the pressure in the gas transfer line, and the pressure causes the power piston to move. The movement of the power piston turns the electric generator in the expansion stroke* (d). *Then the displacer piston is allowed to return to its original position* (a), *and the cycle repeats.*



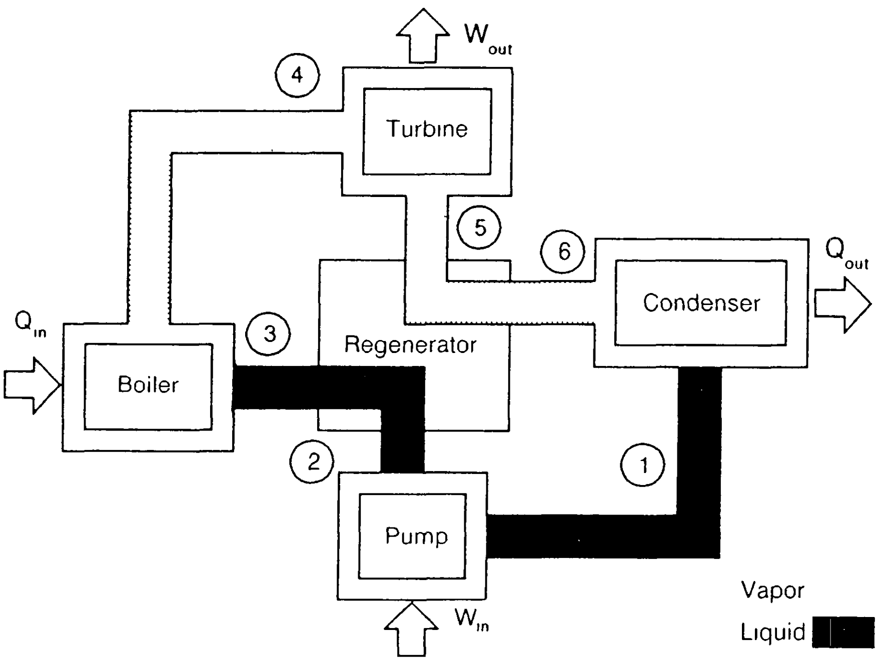


Figure 17

Rankine Cycle

In the Rankine engine, a working fluid (typically an organic liquid) is converted from a liquid to a gas by solar energy and the gas is used to run a turbine connected to an electric generator. The gas is then condensed, recycled, and reheated.

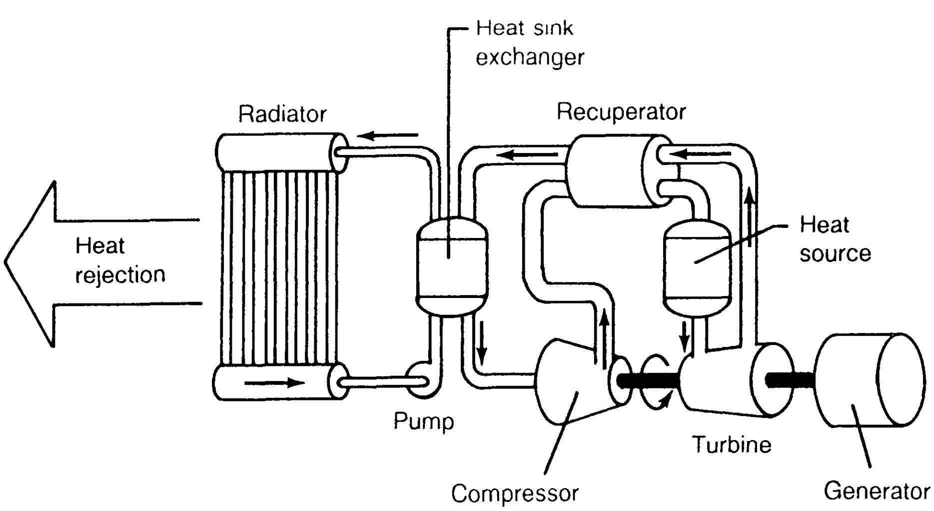


Figure 18

Brayton Cycle

In the Brayton system, power from the gas-driven turbine is used to compress a working gas which is then heated by solar energy to increase its pressure. After passing through the turbine, the gas is cooled in a heat exchanger and recycled through the compressor. In this system, the gas phase is used throughout. All of the systems have efficiencies in the range of 25-35 percent compared to 10-20 percent for direct electric conversion.

Critical system elements are, first, the heat receiver, especially if it includes thermal storage, and, second, lightweight precision collectors operating at 200- to 1000-times concentration. For lunar surface operation during the day, no thermal storage is required. As in the electrochemical storage case, extensive amounts of thermal storage would be required to meet the demands of the 2-week nights. If lunar materials having proper thermal characteristics were available for storage (questionable at this time), it is possible that solar dynamic systems could provide complete power night and day. Further study is required to substantiate this possibility.

Studies on solar Brayton cycles for the LEO space station show that a mirror 21 meters in diameter could produce 80 kW, while a mirror 8.2 meters in diameter could produce 10 kW. Were these size systems to be in continuous sunlight, the comparable powers would be roughly 175 and 22 kW, with system specific powers of 13 and 10 W/kg. Because thermal storage is one-half the total system mass, eliminating such storage (for lunar day-only operation) would increase system specific power to 26 and 20 W/kg, respectively. With system improvements (mirrors, receivers, radiators), and including other Carnot-cycle engines, specific powers around 40 W/kg (with no thermal storage) are possible at operating temperatures between 1100 and 1300 K. With space station support and with long-term advanced research support, high-performance solar dynamic systems could be available by the year 2000.

These systems require that the waste heat be rejected. Thermal management (radiators, heat sinks) remains a critical technology for solar thermal dynamic systems, just as it does for nuclear power systems.

Direct Use of Solar Energy

Many industrial processes have substantial need for high quality thermal energy. Such applications as volatilization, evaporation, and melting can use thermal energy directly, without an electrical intermediary (fig. 19). The basic elements needed are lightweight mirrors and receivers that can collect, distribute, and deliver thermal energy to its point of use. Technology for direct utilization of solar radiation is being developed for terrestrial applications.

Energy Storage

Energy storage is required to provide power for operations during dark times. The nickel-cadmium battery has been the common energy storage companion for solar cells on satellites. Specific energy densities (energy per unit mass) of 10 Whr/kg are common at the 10- to 20-percent depths of discharge used to provide cycle life. As a rule, the energy storage subsystem is the heaviest and largest part of a solar power system. Furthermore, NiCd batteries are sensitive to overcharge; hence, each cell must be carefully controlled. This need poses additional system constraints as power system voltage increases to the 100-kilowatt level and beyond.

Individual pressure vessel (IPV) nickel-hydrogen battery systems are being developed to provide increased energy densities (fig. 20). These batteries provide about 15-20 Whr/kg for GEO

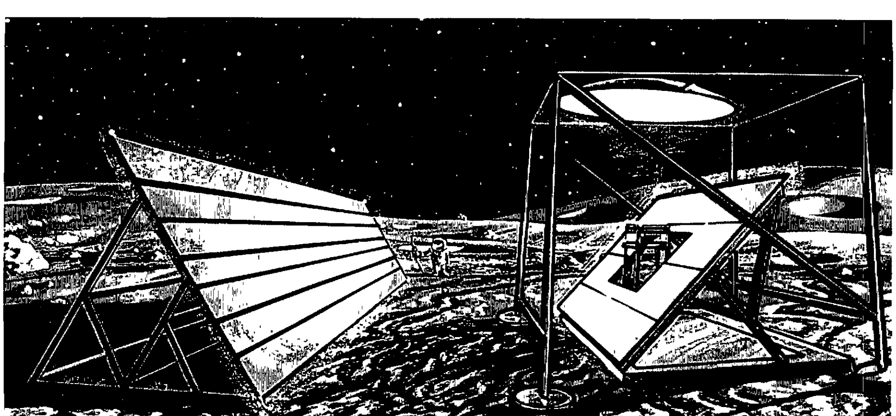
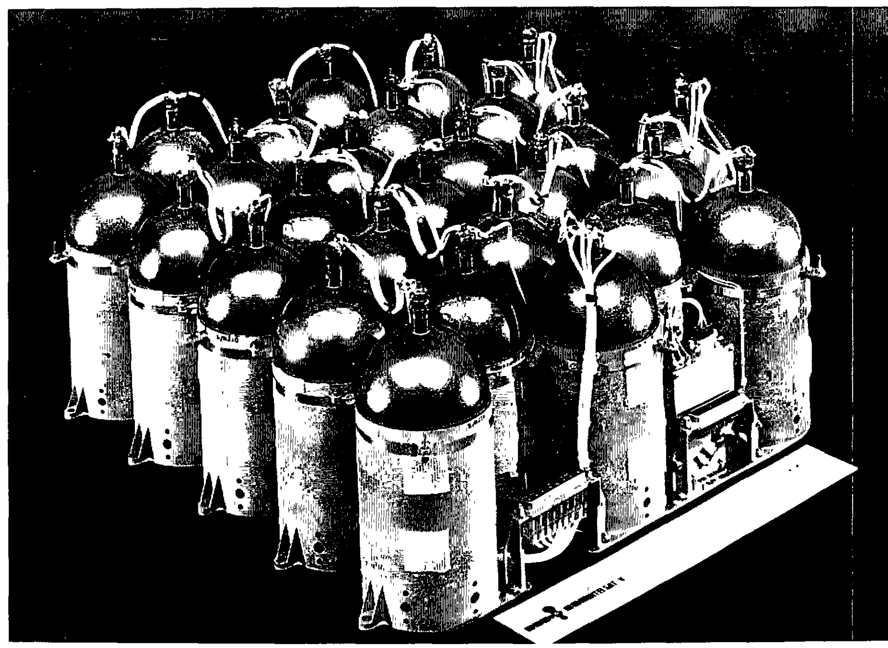


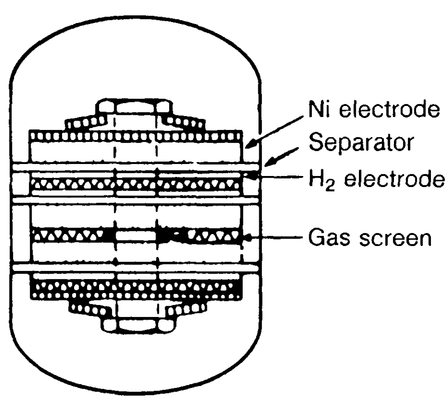
Figure 19

Solar Concentrator System on the Lunar Surface

This system uses a combination of flat and curved mirrors to concentrate sunlight on a furnace. The furnace can be used to extract volatiles, make glass, or melt iron from lunar regolith. Direct use of concentrated solar power can be an important "low tech" source of energy for lunar industrial applications.



System configuration



Pressure vessel cross section

Figure 20

Individual Pressurized Vessel Nickel-Hydrogen Storage Cells

Individual pressure vessel (IPV) nickel-hydrogen (NiH_2) storage cells contain hydrogen under pressure as one electrode of a battery. The other electrode consists of a nickel plate. Such batteries can provide about 15-20 Whr/kg applications. These devices also have applicability to LEO, but they require substantial improvement in cycle life.

There are two high-capacity energy storage systems under consideration for the space station. These are the hydrogen-oxygen regenerative fuel cell (RFC) and the bipolar nickel-hydrogen battery. The former (fig. 21) has a specific energy density of about 20 Whr/kg and an expected cycle life of 5-7 years. Operating voltage level appears reasonably unconstrained, allowing 150 to 300 volts. This technology is suitable for lunar surface exploration and use in GEO or lunar orbit.

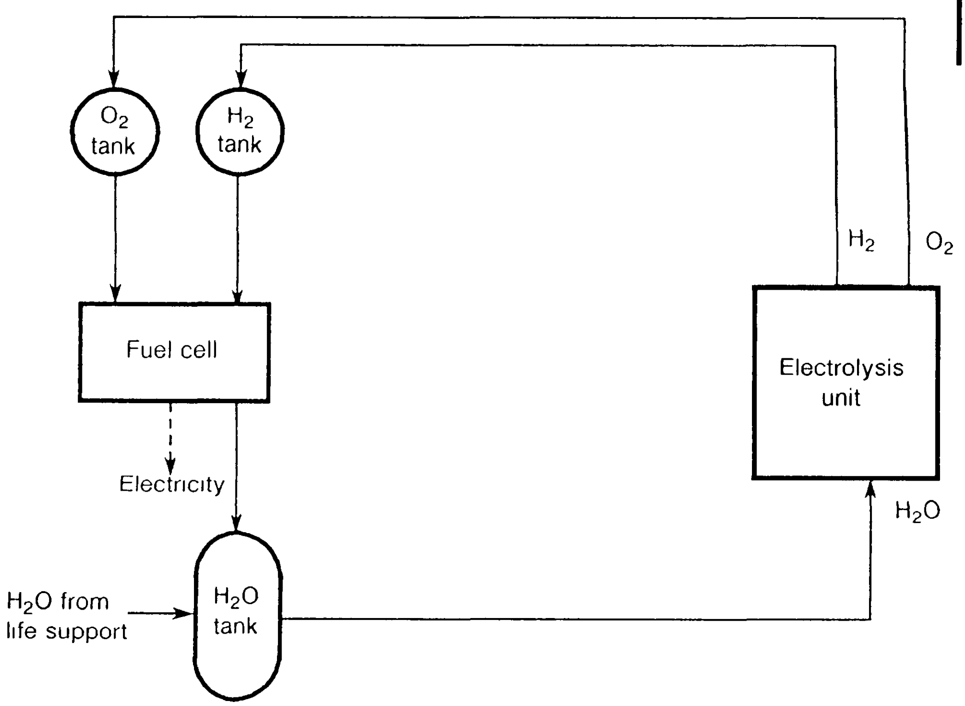


Figure 21

Hydrogen-Oxygen Regenerative Fuel Cell

A hydrogen-oxygen regenerative fuel cell (RFC) system uses electricity supplied from solar cells to electrolyze water into hydrogen and oxygen, which are stored These gases can be used in a conventional fuel cell to generate electricity and produce water as a byproduct. The water can then be recycled through the electrolyzer Specific energy density for such a system is about 20 Whr/kg, and the life cycle is expected to be 5-7 years.

Technology advances may offer energy densities of 1000 Whr/kg to lunar applications. A fuel cell separates power delivered from energy stored. Power is determined by the area of the plates; energy, by the volume of the reactants. Thus, when energy densities of 1000 Whr/kg are combined with lightweight solar arrays and high-voltage power management systems, the overall system promises specific powers near 500 W/kg. It should be noted, however, that the mass of a 1000-Whr/kg storage system to provide 100 kW of power during lunar night would be roughly 33 600 kg.

The bipolar NiH_2 technology marries battery and fuel cell technologies to the benefit of both. Chief advantages are substantially increased cycle life over IPV NiH_2, easy high-voltage battery design by adding more plates, and extremely high discharge capability (20 times charging rate). Bipolar NiH_2 systems appear equivalent in mass to state-of-the-art regenerative fuel cells at 100-kW capacities. However, this technology lags that of the hydrogen-oxygen RFC by several years. Furthermore, substantial improvement in basic understanding and in plate and separator technology is required before these cells can even begin to approach the 1000-Whr/kg potential of the hydrogen-oxygen regenerative fuel cell.

Two additional systems appear capable of high storage densities. These are the rechargeable lithium battery and the hydrogen-halogen (Br, Cl) regenerative fuel cell. Both technologies are in infant stages of development, with issues of materials, cycle life, current densities, separators, and electrolytes. With additional research emphasis, these systems could become available between 1995 and 2000. Because mass is at such a premium on the Moon, and because the energy storage system is the most massive part of a photovoltaic system that supplies continuous power, additional effort should be directed toward innovative energy storage technologies, electrochemical and other.

Flywheels are one example of mechanical energy storage (fig. 22). Although flywheels probably can store in excess of 100 Whr/kg, the overall systems are still heavy (10 Whr/kg) at present. Although these systems may be capable of long lives, this capability has not yet been demonstrated, nor have all failure modes and safety needs been identified.

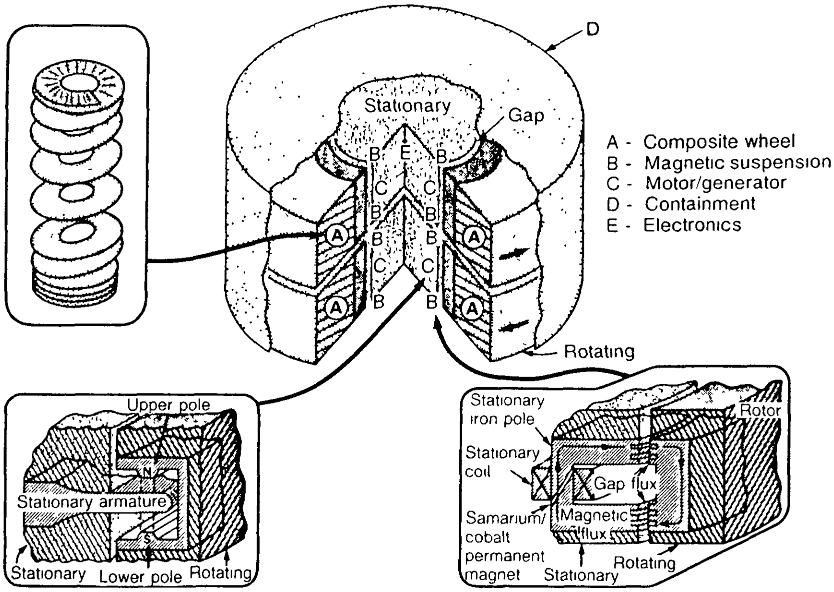
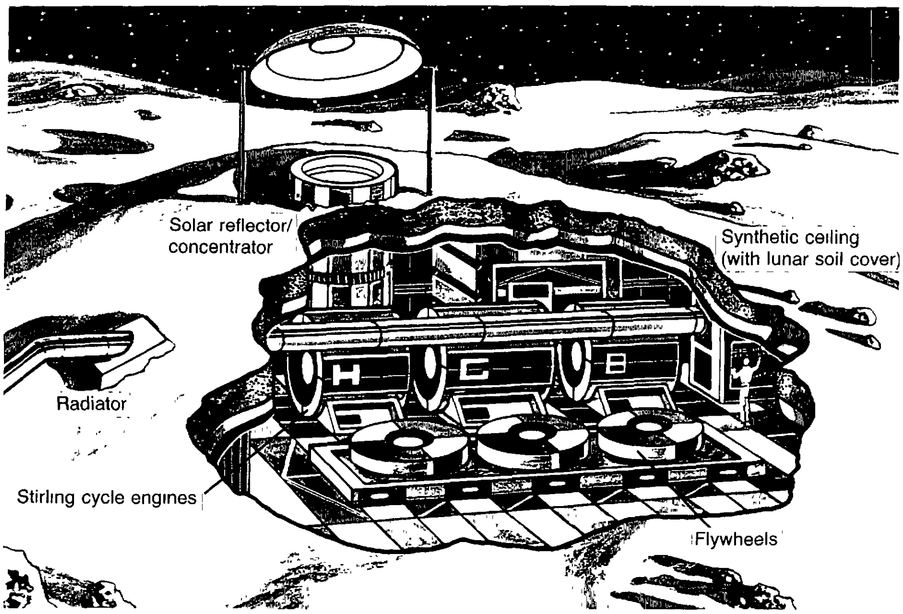


Figure 22

Advanced Flywheel Energy Storage

a. Diagram

This unit has two counter-rotating wheels to reduce torque forces on the system resulting from changes in wheel velocity. Advanced high-strength composites may be used for the wheels. Current designs project an energy storage density of about 100 Whr/kg for these systems.



b. Application

Flywheel storage could be used as a nighttime energy source at a lunar base. Here, solar energy is converted to electricity in Stirling heat engines. The electricity spins up the three large flywheels in the floor. Excess heat is carried away by a heat pipe to a radiator.

Solar dynamic systems also require energy storage for operation during the dark phases of a mission. A number of concepts are being considered. Sensible heat storage (that is, heat stored by the natural heat capacity of the material) in the form of a heat sink mass is one possibility. Another is the use of a material such as a salt which is melted during the solar phase and allowed to freeze during the dark phase, thereby releasing the heat of fusion. Technology development programs are presently under way in the selection of compatible materials and in freeze-thaw phenomena in microgravity.

Within the timeframe of this study, it does not appear that the energy storage technology will be affected by nonterrestrial resources. A variety of candidate technologies with high energy densities have been identified (fig. 23) and must be considered for future energy storage use in GEO and on the Moon.

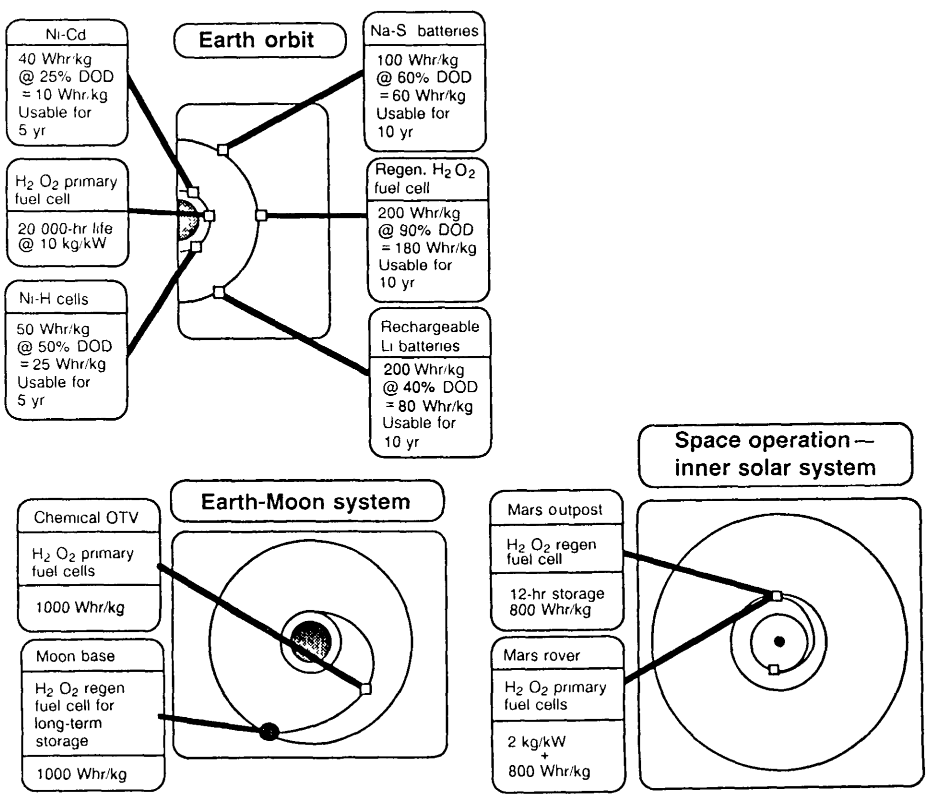


Figure 23

Energy Storage Opportunities 1997

Listed are a variety of energy storage opportunities which will likely be available around 1997. Somewhat different energy storage options are associated with each location. These opportunities are based on current technologies. It is possible that breakthroughs in some of these areas will provide much improved or totally different energy storage possibilities.

Power Management and Distribution

Existing spacecraft power systems are 28 volts dc. This voltage level and type was adequate for the few-kilowatt, dedicated-load missions to date. With the nearly 100-kilowatt electrical power requirements of the space station, however, significantly higher voltage levels and a high-frequency, ac utility-type distribution system are required to deliver this power efficiently to a broad spectrum of national and international users. Compared to existing systems, a 20-kHz ac power management and distribution system provides higher efficiency, lower cost, and improved benefits. The proposed 20-kHz system is based on rapid semiconductor switching, low stored reactive energy, and cycle-by-cycle control of energy flow. This system allows the voltage and wave shapes to be tailored to meet a variety of load requirements, improves crew safety, and provides compatibility with all types of energy sources—photovoltaic, solar dynamic, electrochemical, rotating machines, and nuclear.

Voltage levels on exterior surfaces will likely be set in the 150- to 300-V range by LEO plasma interaction effects. Inside the modules, however, a single-phase, sinusoidal-waveform, 20-kHz distribution system, with a well-regulated 220- or 440-V (root mean square) bus, will minimize wiring mass, transformer weight, conversion steps, and parts. Such a distribution system will provide attendant reductions in the sensing and control complexities required by a redundantly distributed power system with multiple energy sources. Component technology and microprocessor-based innovations in system autonomy will be in hand by the early 1990s to enhance the power system. Requirements pertinent to nuclear systems, such as hardening and high-temperature operation, are being addressed by the SP-100 Program, under which NASA, the Department of Energy, and the Department of Defense are developing space reactor technology.

As power requirements build to the 1- to 10-megawatt level for future space and lunar base missions, however, it is likely that either the bus voltage must leap to the kilovolt level or current levels must increase with paralleling and phase control. In either case, new semiconductors and other components and more switchgear, cabling, and connectors will be required. Designs for operating in the lunar environment, where dust may provide severe environmental interactions, will be especially critical. Early research into all these types of hardware is warranted. We envision that both ac and dc equipment of various types and voltage levels will be routinely used in orbit and on planetary surfaces.

As in the previous cases, it is unlikely that nonterrestrial resources will affect power management and distribution systems by 2010. Rather, it is the power system that will enable utilization of nonterrestrial resources.

Nuclear Energy Technology

David Buden

Radioisotope Generators

Current status: Radioisotope generators use the spontaneous decay of plutonium-238 as a heat source. The energy has traditionally been converted to electricity by means of thermocouples placed next to the heat source. (See figure 24.) Radioisotope generators have been launched in 21 spacecraft, beginning with the successful flight of a space nuclear auxiliary power (SNAP-3A) source in 1961. A summary of launches is shown in table 1.

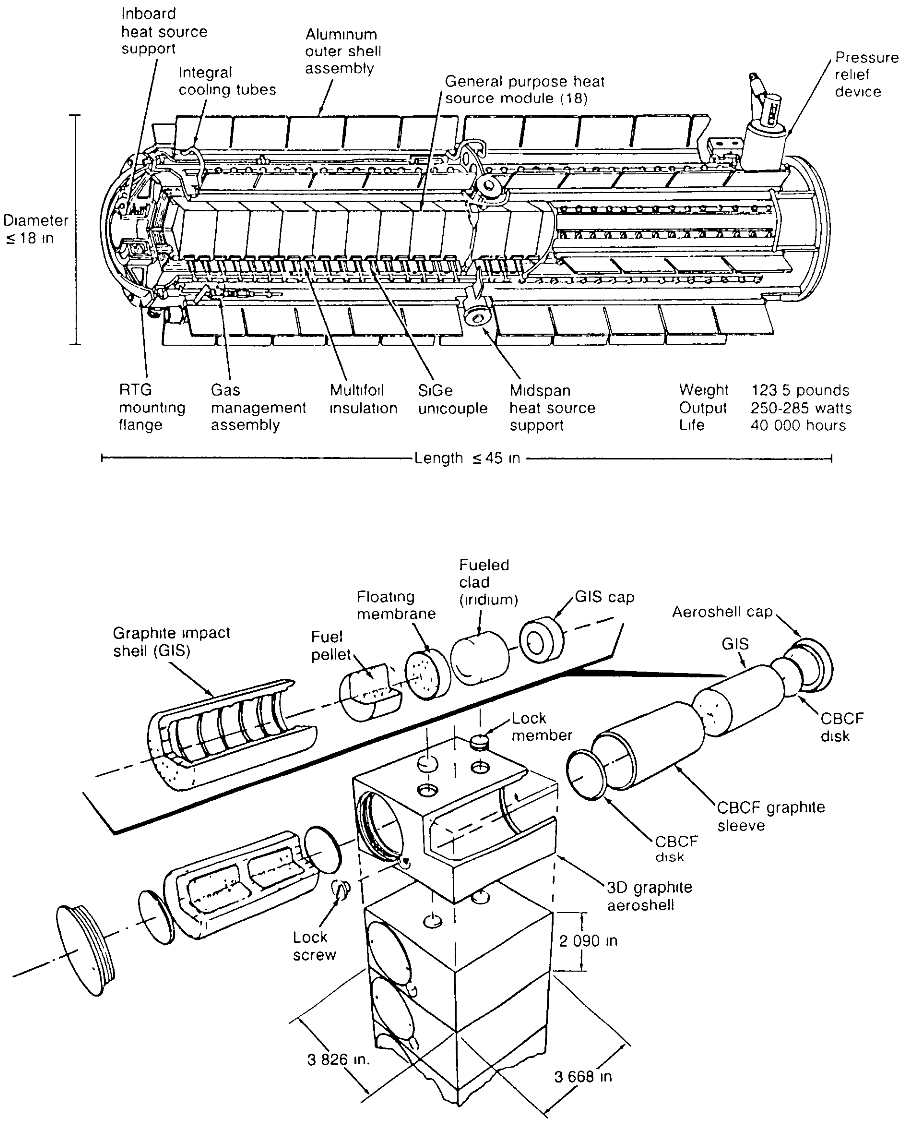


Figure 24

Radioisotope Thermoelectric Generator

This radioisotope thermoelectric generator (RTG) has been built to power the instruments to study Jupiter on the Galileo mission and the poles of the Sun on the Ulysses mission. The plutonium oxide in its 18 general purpose heat source (GPHS) modules decays to heat one end of a silicon-germanium unicouple. The difference in temperature on the two ends of this thermocouple creates an electric current. The detail shows how the pellets of nuclear fuel are clad first in iridium, then in graphite.

TABLE 1. *Summary of Space Nuclear Power Sources Launched by the United States (1961-1980)*

Power source[a]	Spacecraft	Mission type	Launch date	Status
SNAP 3A	Transit 4A	Navigational	June 29, 1961	Successfully achieved orbit
SNAP 3A	Transit 4B	Navigational	Nov. 15, 1961	Successfully achieved orbit
SNAP 9A	Transit 5BN-1	Navigational	Sept. 28, 1963	Successfully achieved orbit
SNAP 9A	Transit 5BN-2	Navigational	Dec. 5, 1963	Successfully achieved orbit
SNAP 9A	Transit 5BN-3	Navigational	Apr. 21, 1964	Mission aborted; burned up on reentry
SNAP 10A	Snapshot	Experimental	Apr. 3, 1965	Successfully achieved orbit
SNAP 19B2	Nimbus B-1	Meteorological	May 18, 1968	Mission aborted; heat source retrieved
SNAP 19B3	Nimbus III	Meteorological	Apr. 14, 1969	Successfully achieved orbit
SNAP 27	Apollo 12	Lunar	Nov. 14, 1969	Successfully placed on lunar surface
SNAP 27	Apollo 13	Lunar	Apr. 11, 1970	Mission aborted on way to Moon; heat source returned to South Pacific Ocean
SNAP 27	Apollo 14	Lunar	Jan. 31, 1971	Successfully placed on lunar surface
SNAP 27	Apollo 15	Lunar	July 26, 1971	Successfully placed on lunar surface
SNAP 19	Pioneer 10	Planetary	Mar. 2, 1972	Successfully operated to Jupiter & beyond
SNAP 27	Apollo 16	Lunar	Apr. 16, 1972	Successfully placed on lunar surface
Transit-RTG	"Transit" (TRIAD-01-1X)	Navigational	Sept. 2, 1972	Successfully achieved orbit
SNAP 19	Pioneer 11	Planetary	Apr. 5, 1973	Successfully operated to Jupiter & Saturn & beyond
SNAP 19	Viking 1	Mars	Aug. 20, 1975	Successfully landed on Mars
SNAP 19	Viking 2	Mars	Sept. 9, 1975	Successfully landed on Mars
MHW	LES 8/9[b]	Communications	Mar 14, 1976	Successfully achieved orbit
MHW	Voyager 2	Planetary	Aug. 20, 1977	Successfully operated to Jupiter & Saturn & beyond
MHW	Voyager 1	Planetary	Sept. 5, 1977	Successfully operated to Jupiter & Saturn & beyond

[a]SNAP 10A was powered by a nuclear reactor, the remainder were powered by radioisotope thermoelectric generators
[b]LES = Lincoln experimental satellite

The technical characteristics of these radioisotope generators are listed in table 2. Their reliability and long life is demonstrated by the Pioneer satellite, which after 11 years of operation left our solar system still functioning. The recent magnificent pictures of Saturn taken from the Voyager spacecraft powered by radioisotope generators are also testimonials to the longevity and reliability of this type of power supply. (See figure 25.)

Radioisotope thermoelectric generators (RTGs) have been used where long life, high reliability, solar independence, and operation in severe environments are critical. Economic considerations have restrained them from more general use.

TABLE 2. *Radioisotope Generator Characteristics*

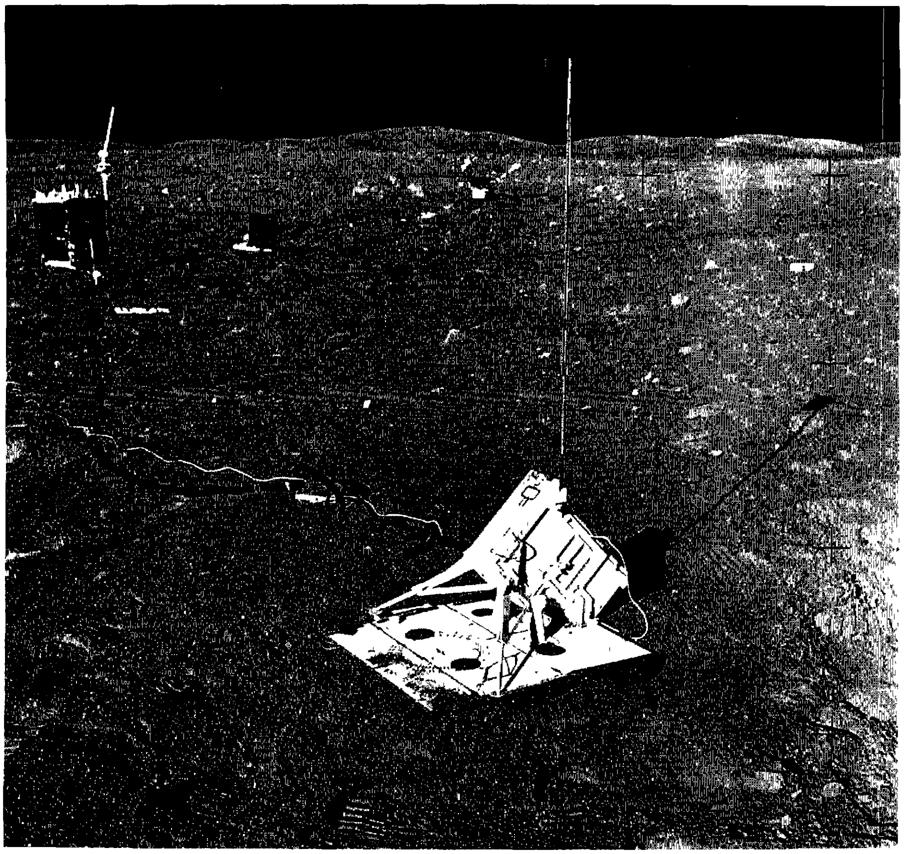
	SNAP 3A	SNAP 9A	SNAP 19	SNAP 27	Transit-RTG	MHW	GPHS-RTG	DIPS
Mission	Transit	Transit	Nimbus Pioneer Viking	Apollo	Transit	LES 8/9 Voyager	Galileo	
Fuel form	Pu metal	Pu metal	PuO_2-Mo cermet	PuO_2 microspheres	PuO_2-Mo cermet	Pressed PuO_2	Pressed PuO_2	Pressed PuO_2
Thermoelectric material	PbTe	PbTe	PbTe-TAGS	PbSnTe	PbTe	SiGe	SiGe	Organic Rankine
BOL output power watts (e)	2.7	26.8	28-43	63.5	36.8	150	290	1300
Mass, kg	2.1	2.2	13.6	30.8[a]	13.5	38.5	54.4	215
Specific power, W_e/kg	1.3	2.2	2.1-3.0	3.2[b]	2.6	4.2	5.2	6.0
Conversion efficiency, %	5.1	5.1	4.5-6.2	5.0	4.2	6.6	6.6	18 1
BOL fuel inventory watts (t)	52	565	645	1480	850	2400	4400	7200
Fuel quantity, curies	1800	17 000	34 400-80 000	44 500	25 500	7.7×10^4	1.3×10^5	2.1×10^5

[a]Without cask.
[b]Includes 11 1-kg cask
RTG = radioisotope thermoelectric generator
GPHS = general purpose heat source
DIPS = dynamic isotope power system
TAGS = telluride antimony germanium silver
BOL = beginning-of-life

Figure 25

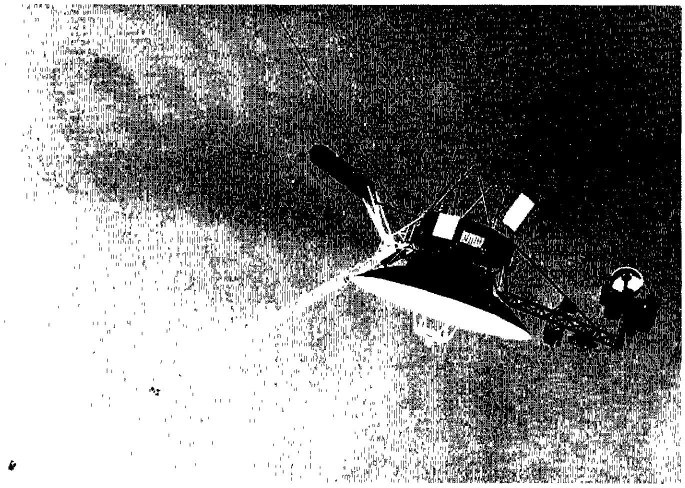
Experiments and Spacecraft Powered by RTGs

A number of scientific experiments and spacecraft have been powered by radioisotope thermal generators (RTGs).



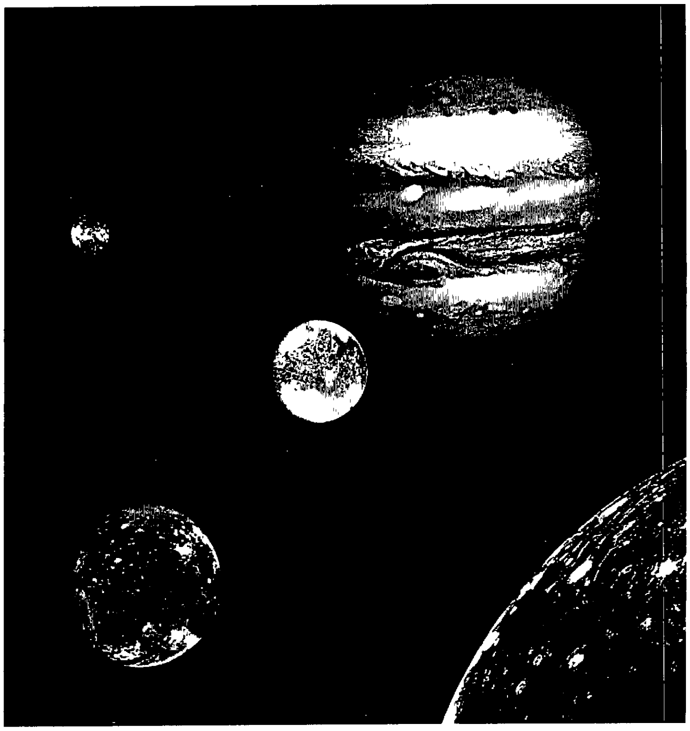
a. Apollo Lunar Surface Experiments Package (ALSEP)

The Apollo missions included lunar surface experiments powered by RTGs. One of them, a seismic mortar, is shown in the foreground of this photo connected by cables to the central control and communications unit in the background. The whole package of experiments was powered by the finned RTG, which appears to the right of the control and communications unit. The RTG units proved reliable and powered the instruments left on the surface of the Moon for years after the astronauts returned. These nuclear power generators also proved safe; one even survived the reentry of the Apollo 13 Lunar Module (LM).



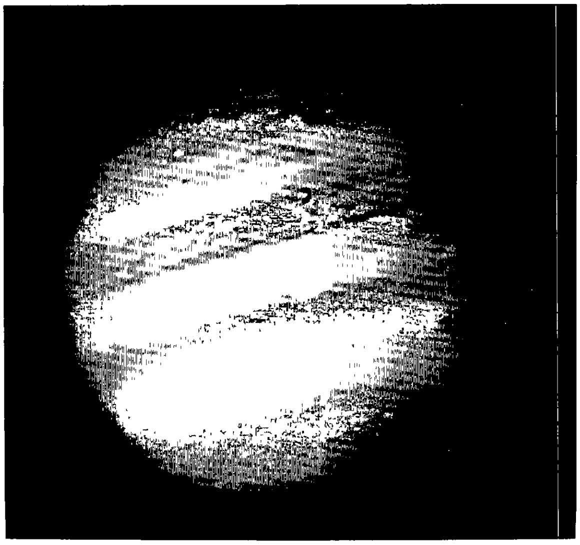
b. Voyager

RTG units were also used to power the Voyager spacecraft to Jupiter, Saturn, and the outer planets.



c. Jupiter and Its Moons

This composite photograph shows the moons of Jupiter, not to scale but in their relative positions: Io (upper left), Europa (center), Ganymede (lower left), and Callisto (lower right).

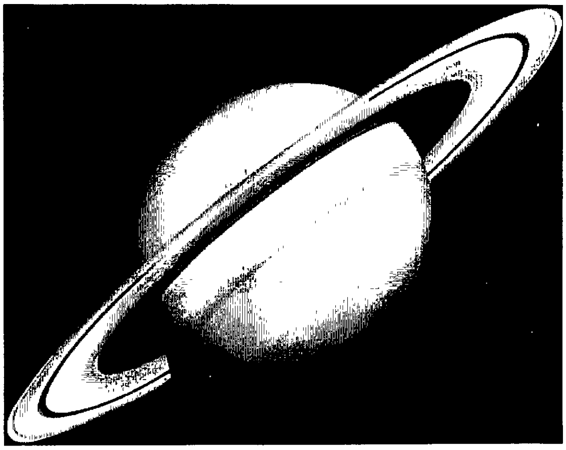


d. Io Moving Across the Face of Jupiter

In this dramatic view captured by Voyager 1's camera, the moon Io can be seen traveling across the face of Jupiter and casting a shadow on the giant planet.

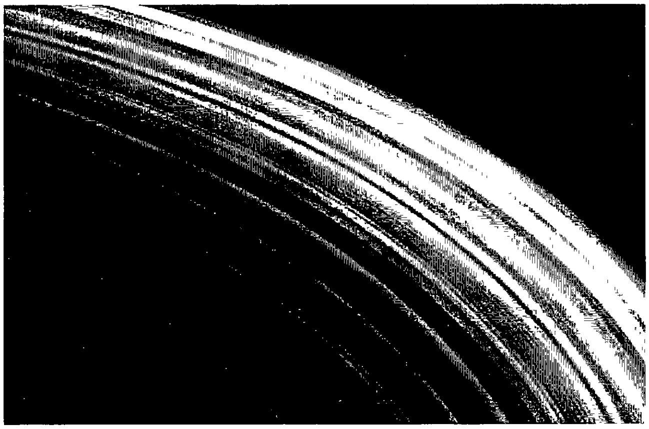
e. Saturn

Saturn was also photographed by Voyager using RTG power. Here is a full view of the second largest planet and its ring system.



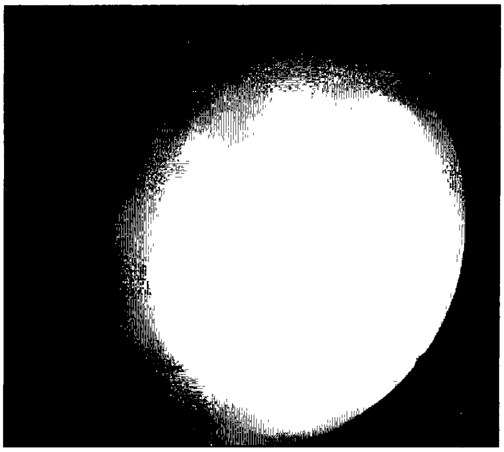
f. The Rings of Saturn

Voyager revealed for the first time a faint ring of particles around Jupiter and provided closeups of the well-known rings of Saturn, showing details of the intricate structure of these rings.



g. Uranus

Uranus also was photographed by the RTG-powered Voyager 2 in 1986.



Future developments: Improved versions of the RTG will have better performance. However, RTGs will probably be restricted to under 500 W. Higher power levels of maybe 5-10 kW_e are possible by using dynamic converters for power conversion. A 1.3-kW_e version was tested for several thousand hours before the program was terminated. A revised program to cover the 1-10 kW_e range is scheduled to start in 1988. These improved versions using thermocouples and dynamic converters could be used for lunar and Mars rovers and explorations away from lunar camps and bases.

Nuclear Reactor Power Plants

Current status: The current U.S. effort to develop nuclear reactors for space is centered in a program entitled "SP-100," which is a joint program of the Department of Defense, the Department of Energy, and NASA. (SP-100 is not an acronym.)

The decision to proceed with the construction of a specific space nuclear power plant was made and a contractor selected in 1986. The program has completed the critical technology development and assessment phase. Activities centered around evaluating promising space reactor concepts and determining which technologies are most likely to achieve the required performance levels. The technology assessment and development phase included defining mission requirements, doing conceptual designs of possible systems, and researching and developing critical technologies.

Following screening by the SP-100 Program of over a hundred potential space nuclear power system concepts, the field was narrowed to three candidate systems which appear to meet the requirements in table 3 without unreasonable technical risks or development time.

One concept uses a fast-spectrum, lithium-cooled, cylindrical, pin-type-fuel-element reactor with thermocouples for power conversion (fig. 26) (General Electric Co. 1983). The system is made up of a 12-sided cone structure with a 17-degree cone half angle. The reactor, which is a right-circular cylinder approximately 1 meter in diameter and 1 meter high, is at the apex of the conical structure. It is controlled by 12 rotatable drums, each with a section of absorbing material and a section of reflective material to control the criticality level. Control of the reactor is maintained by properly positioning the drums. The reactor outlet temperature is 1350 K.

TABLE 3. *SP-100 Goals*

Performance	
Power output, net to user, kW_e	100
Output variable up to 100 kW_e	
Full power operation, years	7
System life, years	10
Reliability	
1st system, 2 years	0.95
Growth system, 7 years	0.95
Multiple restarts	
Physical constraints	
Mass, kg	3000
Size, length within STS envelope, m	6.1
Interfaces	
Reactor-induced radiation after 7 years' operation, 25 m from forward end of reactor	
Neutron fluence, n/cm^2	10^{13}
Gamma dose, rads	5×10^5
Mechanical	STS launch conditions
Safety	Nuclear Safety Criteria and Specifications for Space Nuclear Reactors

The shield is mounted directly behind the reactor and consists of both a gamma and a neutron shield. The gamma shield consists of multiple layers of tungsten designed so as to prevent warping. The neutron shield is made up of a series of axial sections with thermal conductors between them. The thermal conductor carries the gamma- and neutron-generated heat to the shield surface, where it is radiated to space. Anticipated temperature levels are 675 K, maximum.

Thermal transport is accomplished by thermoelectrically driven electromagnetic pumps. The thermocouples for the pumps are powered by the temperature drop between the working fluid and the pump radiators. This approach assures pumping of the working fluid as long as the reactor is at temperature, and it facilitates the cooldown of the reactor when power is no longer required.

The reactor's thermal interface with the heat distribution system is through a set of heat exchangers. In this way, the reactor system is self-contained, can be fabricated and tested at a remote facility, and can be mated to the power system

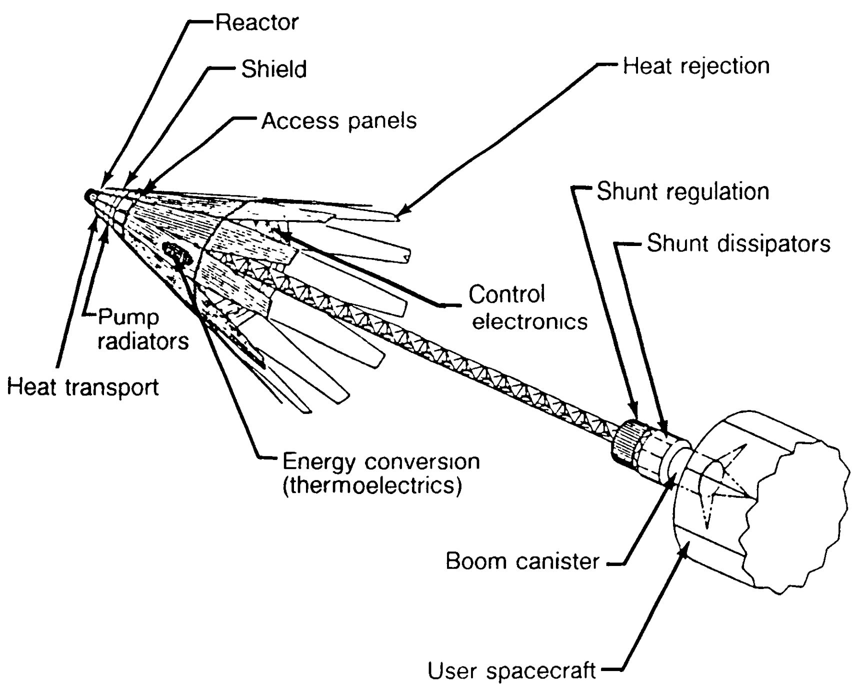


Figure 26

Concept of High-Temperature Reactor With Thermoelectric Power Conversion

downstream. Access panels are provided on the main body to facilitate the connection of the heat distribution system to the heat exchanger.

Thermoelectric elements for converting thermal energy to electric power are bonded to the internal surfaces of the heat rejection panels and accept heat from the source heat pipe assembly.

The heat rejection surfaces are beryllium sheets with titanium-potassium heat pipes brazed to the surface to distribute and carry the heat to the deployable panels, which are needed for additional heat rejection. The deployable panels are thermally coupled through a heat-pipe-to-heat-pipe thermal joint, which is very similar to the source-heat-pipe-to-heat-exchanger joint, made integral by the use of special materials that are self-brazing in orbit. To allow the deployment of the panels, a bellows-like heat pipe section is mounted at the tail end of the heat pipes on the fixed panel. Such a flexible heat pipe has been demonstrated.

The system has a wide range of flexibility. Its output can be expanded either by increasing the thermoelectric efficiency or by increasing the size and weight of the system. The potential for scaling up the system is shown in figure 27 (Katucki et al. 1984).

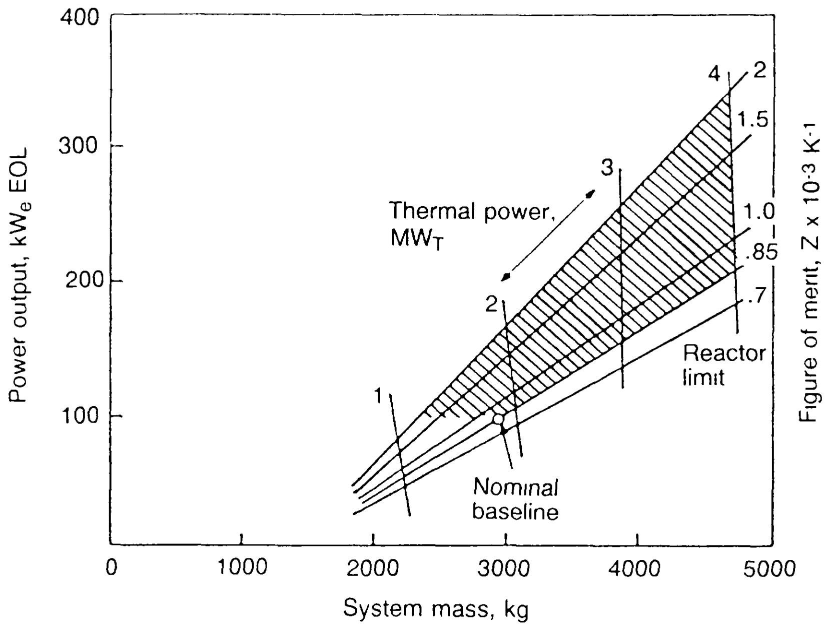


Figure 27

Scalability of Concept of High-Temperature Reactor With Thermoelectric Conversion

A second approach evaluated is an in-core thermionic system with a pumped sodium-potassium eutectic coolant (GA Technologies and Martin Marietta 1983). The general arrangement of this space power system design is shown in figure 28. The design forms a conical frustum that is 5.8 m long, with major and minor diameters of 3.6 m and 0.7 m. The reactor-converter subsystem includes the reactor, the reflector/control drums, and the neutron shield. The reactor contains the thermionic fuel element (TFE) converters within a cylindrical vessel, which is completely surrounded by control drums.

The hot NaK leaves the reactor at the aft end and the cold NaK is returned to the forward end, thus minimizing differential thermal expansion in the piping. The reactor is also surrounded by an array of long, thin cylindrical reservoirs that collect and retain the fission gases generated in the reactor core during the operating

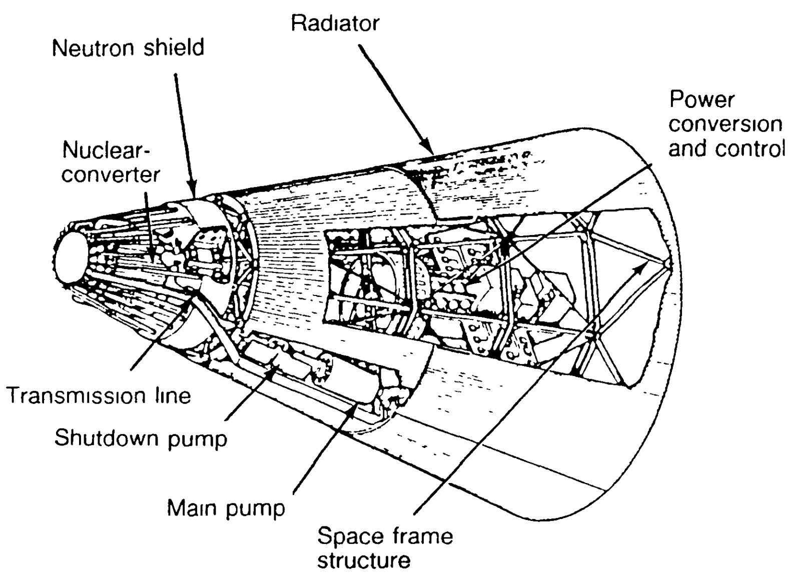


Figure 28

Concept of In-Core Thermionic Power Plant

life of the system. Waste heat is removed from the primary loop through the heat exchanger. The energy is transferred through the heat-sink heat exchanger to heat pipes that form the radiating surfaces for rejection of heat to space.

Within the reactor vessel are 176 TFEs, a grid plate to support the TFEs at one end, a tungsten gamma shield, and the eutectic NaK coolant. Each TFE is welded into the flattop head of the vessel but allowed to move axially in the grid plate. Expansion is expected to be small, since the TFE sheath tubes and reactor vessel are both made of an alloy of niobium and 1 percent zirconium and their temperatures are nearly the same.

The TFE consists of six cells connected in series with end reflectors of beryllium oxide. Boron carbide neutron absorber is placed at both ends of the fuel element to reduce the thermal neutron flux in the coolant plenums and in the gamma and neutron shields. This reduces activation of the coolant, secondary gamma ray production, and nuclear heating of the lithium hydride shield.

The individual cells (see fig. 29) are connected in series to build up voltage from the 0.4-V cell output. Electrical power is generated in

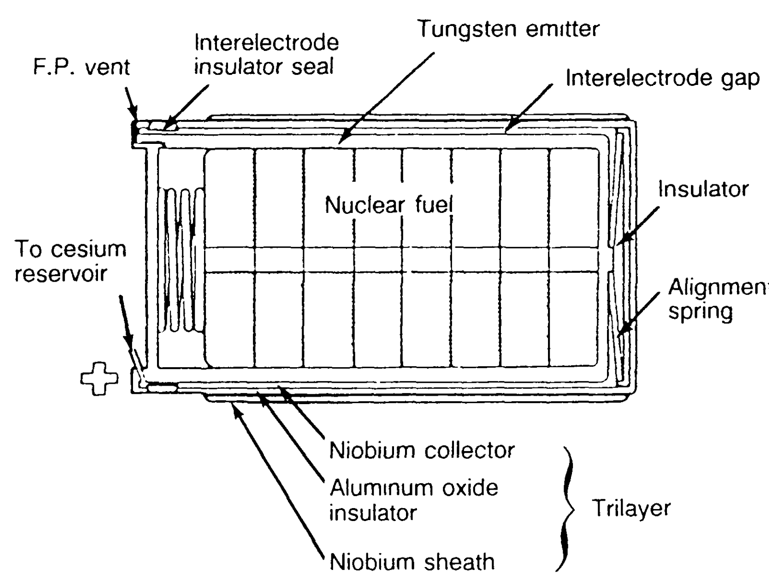


Figure 29

In-Core Thermionic Converter

the space between the tungsten emitter and the niobium collector, and the electrical current output is conducted from one cell to the next through the tungsten stem of the emitter and the tantalum transition piece. The UO_2 fuel is held in place and supported during launch by a retention device designed to retract when the fuel expands upon heating. The alignment spring at the base of the emitter centers the emitter in the collector to maintain a uniform interelectrode spacing. It also restrains the emitter against launch vibration to prevent large displacements and limit stresses in the thin stem at the other end of the emitter.

Fission gases are vented from the UO_2 fuel to prevent the buildup of pressures that would cause creep deformation of the tungsten emitter and close the interelectrode space. Fission gases are kept separate from the cesium (used to reduce the space charge effect) by the ceramic-to-metal seal and the arrangement of passages through the emitter cap and transition piece.

Reactor control is provided by the rotation of the 20 cylindrical control drums surrounding the reactor. The heat transport subsystem is a single loop that includes all of the NaK plumbing aft of the reactor, the heat-sink heat exchanger, and the radiator. The 100-mm-diameter NaK lines to and from the reactor are routed inside helical grooves in the outer surface of the neutron shield and then pass along the inside surface of the radiator to connect to the heat-sink heat exchanger. The configuration of the NaK lines along the shield is helical, rather than straight, to avoid degradation of the shield performance due to neutron streaming in the pipe channels.

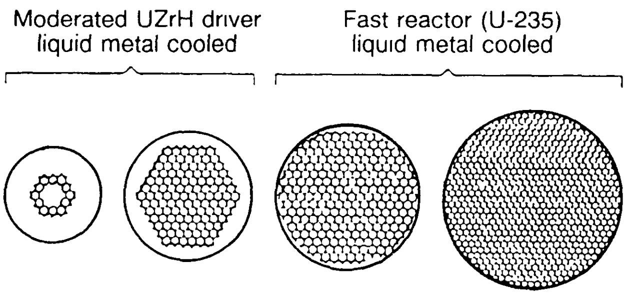
The helical channels in the shield are also occupied by the electrical transmission lines, which are flattened in cross section and are routed over the NaK lines to serve as meteoroid protection. Electromagnetic pumping is used to circulate the NaK during normal operation and during shutdown. Two electromagnetic pumps are provided in the cold leg of the NaK circuit: an annular linear-induction pump to serve as the main pump and a parallel thermoelectromagnetic pump (with a check valve) to provide shutdown pumping capability.

The radiator contains two finned heat pipe assemblies, which form a conical frustum when the panels are assembled on the radiator structure. The heat pipes follow the slant height of the core and are deployed fore and aft of the heat-sink heat exchanger, to which they are thermally coupled. The radiator provides environmental protection for the equipment it houses.

Growth is possible by either redesigning the reactor with more TFEs or increasing the emitter temperature (see fig. 30) (Katucki et al. 1984). An upper temperature level of about 2000 K is believed to be an operational limit for the tungsten emitter.

The third approach uses a Stirling engine to convert to electricity heat from a lower temperature (900 K), fuel-pin-type reactor. This design emphasizes the use of state-of-the-art fuel pins of stainless steel and UO_2, with sodium as the working fluid. Such fuel pins have been developed for the breeder reactor program, with 1059 days of operation and 8.5-percent burnup demonstrated.

The reactor can be similar in design to the high-temperature reactor, but it utilizes lower temperature materials. In figure 31 (General Electric Co. 1983), the reactor is constructed as a separate module from the conversion subsystem. Four Stirling engines, each rated to deliver 33 kW_e, are included in the design concept to provide redundancy in case of a unit failure. Normally the engines operate at 75 percent of rated power to produce an output of 100 kW_e. Each engine contains a pair of opposed-motion pistons, which operate 180 degrees out of phase. This arrangement eliminates unbalanced linear



kW_e	10	50	100	1000
Core diameter, cm	~33	~45	~50	~60

Figure 30

Scalability of In-Core Thermionic Reactor

momentum. Each engine receives heat from a pumped loop connected to the reactor vessel.

An alternate arrangement would deliver the heat through an interface heat exchanger with heat pipes between the heat exchanger and the engine. Waste heat is removed from the cooler heads and delivered to a liquid-to-heat-pipe heat exchanger. The heat pipes, in turn, deliver the waste heat to the radiator where it is rejected to space.

Figure 32 provides performance curves for the Stirling system. A low temperature will meet the goal of 100 kW_e. However, growth systems favor combining the Stirling engines with higher temperature reactors both to minimize mass and to reduce heat rejection surface areas.

Figure 33 summarizes the mass and specific power projected for the 100-kW_e class of power plants.

The fast-spectrum, lithium-cooled reactor with thermoelectrics (concept 1) has been selected for the ground demonstration system. Work is continuing on thermionic fuel element development and Stirling engine development for possible use in growth versions of SP-100.

Future developments: Several classes of reactor power plants will be needed in the future to provide adequate energy for lunar camps and base stations, the growth space station and Space Station 2, and electric propulsion. The 50- to 1000-kW_e power plant being developed by the SP-100 Program for flight in the early to mid-1990s will meet the power

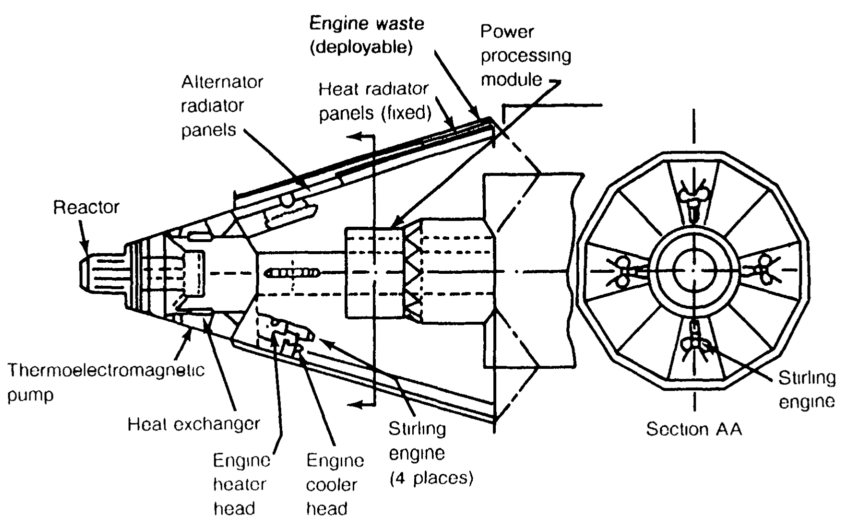


Figure 31

Concept of Stirling Engine Conversion

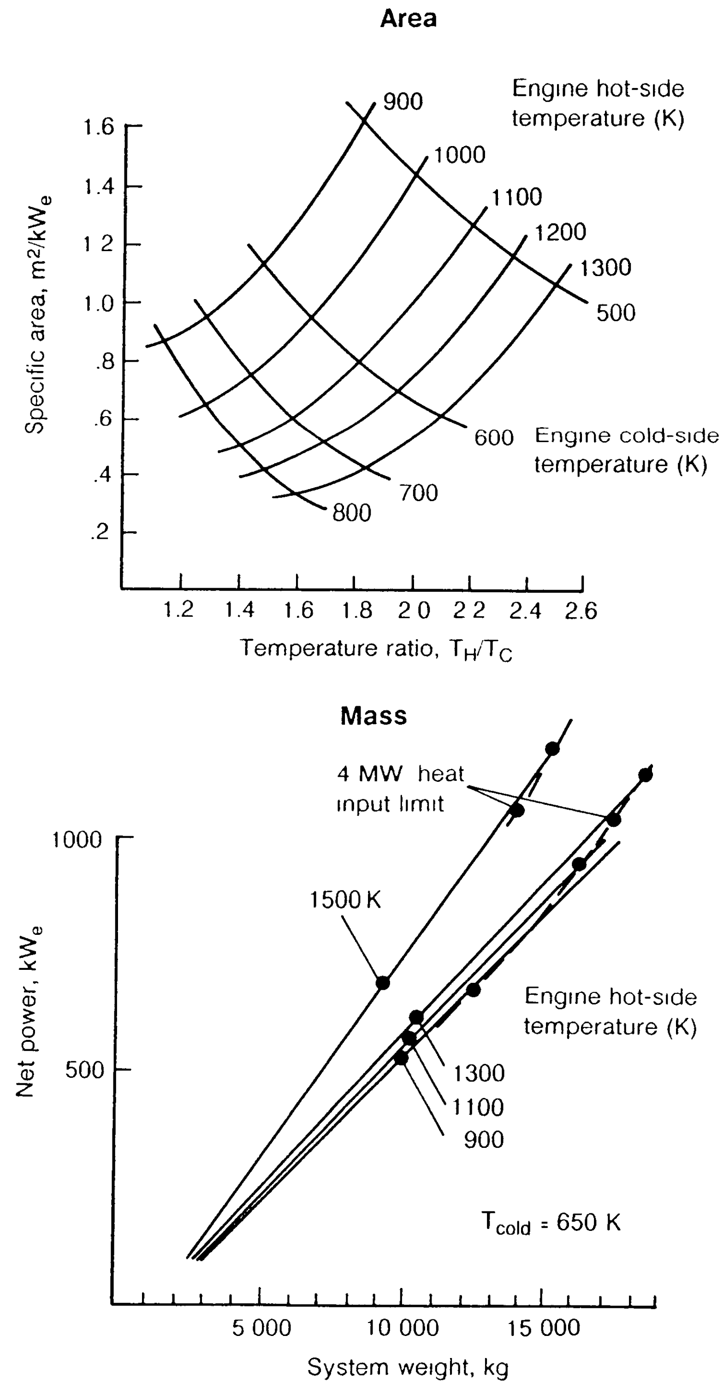


Figure 32

Scalability of Stirling Power System Concept

requirements of the growth space station, the lunar surface day/night camp, and nuclear electric propulsion. However, the requirements and designs have been aimed at unmanned systems. These should be reviewed and modified as necessary to meet manned operational requirements. These requirements could include shielding that completely encloses the reactor, additional emphasis on shutdown heat removal and safety systems that are independent and redundant, and considerations of maintainability and disposal.

We anticipate that the early lunar camps and bases will involve the transport of a space station version of the 100-kW_e-class power plant with little shielding. The power plant would be arranged to reject heat to space. People would be protected by using lunar materials for the radiation barrier.

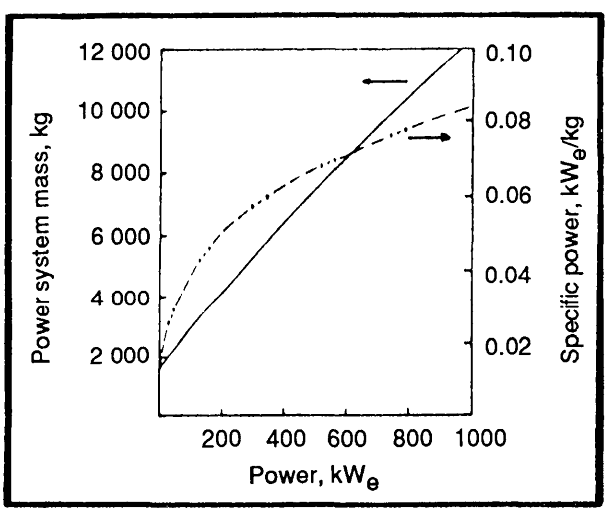


Figure 33

Performance Projections for Space Nuclear Reactor Power System

Space Station 2, requiring 1-10 MW_e, would need a new class of reactor plants. Major changes in reactor designs may be called for, such as higher temperatures, refuelability, and maintainability of certain components. Significant improvements in power conversion and heat rejection are also necessary. The power conversion will probably work at a higher temperature; innovative design through in-core thermionics is being evaluated as an alternative. Heat rejection will need a deployable system that uses a nonarmored radiator technology. One concept, the liquid droplet radiator, is now being pursued to demonstrate technology feasibility. Other concepts include belts, balloons, and rollup heat pipes. The goal would be to package a 10-MW_e power plant in a single Shuttle launch.

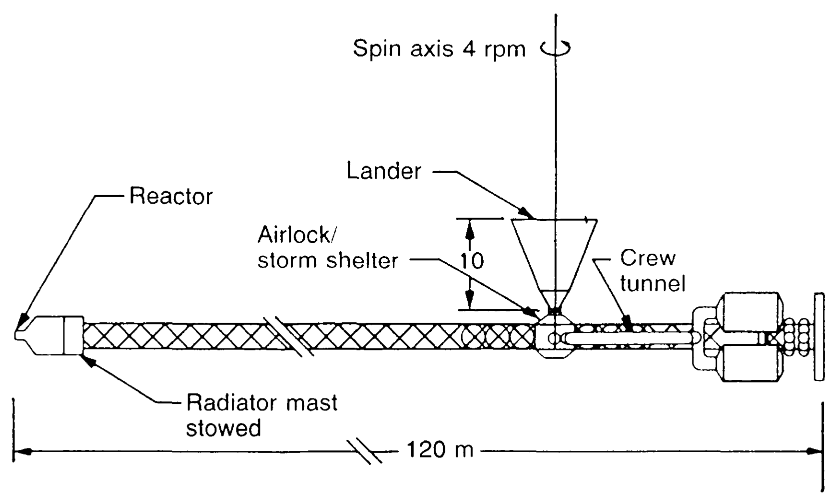
The power plant for Space Station 2 can meet the requirements for a manned Mars mission (fig. 34) and for a lunar orbital transfer vehicle using nuclear electric propulsion. For the advanced lunar base, the same power plant could be

Figure 34

Manned Mars Mission

After a 600-day flight to Mars, a 100-day reconnaissance phase is initiated, during which a crew will land and investigate Mars for 1 month. The return trip to geosynchronous Earth orbit (GEO) takes about a year.

Using this configuration and conducting a mission of this sort would require 6 MW of power operating for 14×10^3 hours and thus expending an energy total of 8×10^7 kWhr.



used. Again, lunar soil could provide shielding. However, if a mining and materials fabrication capability were in place, it could be used to fabricate a specially designed heat rejection subsystem. Doing so could produce a major savings in mass transfer from Earth. Several innovative designs are possible, such as continuous ejection and collection of fluid or solid particles.

Public Safety and the Use of Nuclear Reactors in Space

Policy and goals: The policy of the United States for all U.S. nuclear power sources used in space is to ensure that the probability of release of radioactive materials and the amounts released are such that an undue risk is not presented, considering the benefits of the mission (U.S. Department of Energy 1982). Safety criteria are specified for the design of the SP-100 space nuclear reactor power plant; safety is to be built into the design, not just added on.

The restriction of radiation exposure (DOE 1982) depends on reducing the probability of an accident that might release radioactive materials into the environment and on limiting the magnitude of such a release should one occur.

Space nuclear power applications must keep the radiation exposure of astronauts, occupational workers (e.g., ground support personnel), and members of the general public "as low as reasonably achievable" during all mission phases, normal and abnormal. According to recommended standards (U.N. General Assembly paper 1980), the maximum accumulated doses for closely involved workers and for the general population are those listed in table 4. Allowable doses for astronauts are generally in the same range as those allowed for radiation workers.

TABLE 4. *Normal Mission Exposure Limits*

Type of exposure	Condition	Dose, rem
Individuals in controlled area:		
Whole body, head and trunk, active blood-forming organs, gonads, or lens of eye	Accumulated dose Calendar quarter	5(N-18)* 3
Skin, thyroid, and bone	Year Calendar quarter	30 10
Hands and forearms, feet and ankles	Year Calendar quarter	75 25
Other organs	Year Calendar quarter	15 5
Individuals in uncontrolled areas:		
Whole body, gonads, or bone marrow	Annual dose to critical individuals at points of maximum probable exposure	0.5
Other organs	Same	1.5
Whole body, gonads, or bone marrow	Average annual dose to a suitable sample of the exposed population	0.17
Other organs	Same	0.5

* Where N equals age in years at next birthday

rem or "roentgen equivalent man" = the dose which produces an equivalent probability of harmful radiation effects

1 rem = 1 cSv

The safety program is designed to protect the public against exposure to radiation levels above established standards. This can be accomplished by preventing accidental reactor criticality and by avoiding release of radioactive byproducts into the biosphere in sizes and concentrations that exceed the standards.

Another set of safety goals encompasses the protection of investments in facilities both on the ground and in space. These facilities must be protected both because they are national assets that would be costly to replace and because a failure would produce significant delays in our national efforts to build the space station. Safety goals and requirements are summarized in table 5.

TABLE 5. *Safety Goals and Requirements*

Goals	Reasons	Design requirements
Assure the existence of normal conditions before launch to avoid special handling or precautions.	To protect workers and astronauts	The reactor shall not be operated (except for zero power testing) until a stable orbit or flight path is achieved.
		There must be two independent systems to reduce reactivity to a subcritical state.
		Unirradiated fuel shall pose no significant environmental hazard.
Prevent inadvertent criticality.	To ensure that the public is not exposed to levels of radiation that exceed standards	The reactor must remain subcritical if immersed in water or another fluid.
	To protect the Shuttle crew	The reactor must have a significant negative power coefficient.
		The reactor must be subcritical in an Earth-impact accident.
		A reactor safety system must be incorporated.
		There must be quality assurance standards.
		A positive-coded telemetry system must be used for reactor startup.
		There must be redundant control and safety systems.
		There must be independent sources of electrical power for the reactor control system, the reactor protection system, and the reactor communication system.
		There must be instrumentation to continuously monitor reactor status.
Avoid release of radioactive byproducts in concentrations exceeding radiological standards.	To ensure that the public is not exposed to radiation levels that exceed standards and to protect the biosphere against concentration of radioactive elements above safety standards	An orbital boost system must be provided for short-lived orbits.
		There must be spacecraft attitude controllers for the communication and boost systems.
Avoid unplanned core destruction.	To protect space investments and to avoid contamination of volumes of the space environment	An independent system for decay heat removal must be provided for shutdown situations.
		There must be two independent systems to reduce reactivity to a subcritical state.
		A positive-coded signal must be used to operate the reactor.
		There must be two independent reactor protection systems.
		Fault-detection systems must be provided for the reactor protection systems.

The safety review process: The United States requires an analysis of each space mission involving nuclear material to assess the potential radiological risk to the biosphere. The process begins when the space mission is defined and the design is conceived. The safety review process continues through launch safety analysis, approval to launch, and proper nuclear power source disposal.

The developer of the nuclear power source is responsible for performing the nuclear safety analyses for the system. Results of these safety analyses are reported at least three times during the development cycle in documents entitled Preliminary Safety Analysis Report (PSAR), Updated Safety Analysis Report (USAR), and Final Safety Analysis Report (FSAR).

The Preliminary Safety Analysis Report is issued 120 days after a design concept is selected. It contains a description of the design, a failure mode analysis, and a nuclear safety analysis. The latter two requirements are based on the safety research data for the development of heat sources, historical heat source design information, and the requirements set forth in the guidelines written by the Department of Energy (DOE). At this stage of system development, the failure mode analysis is based on the response to potential accident environments and on design limitations established by the guidelines.

The Updated Safety Analysis Report is issued 90 days after the design is set. It is similar in format to the preliminary report. Additional requirements include a description of the mission on which the system is to be used and an update of the failure mode analysis using data from the developmental tests performed to set the design.

The Final Safety Analysis Report is issued approximately 1 year before the scheduled launch and is similar in format to the earlier reports. This report provides final system, mission, and safety assessment data, factoring in the results of the verification and qualification test programs. Thus, the final assessment is based on the actual mission environments.

The Interagency Nuclear Safety Review Panel (INSRP) is responsible for review of the safety analysis reports at each step of the development process. The end result of the INSRP process is the Safety Evaluation Report (SER). This report evaluates potential human exposures to radiation and the probabilities of exposure during all phases of the mission. The INSRP submits the Safety Evaluation Report to the heads of the Department of Energy, NASA, and the Department of Defense for their review. The head of the agency that wants to fly the nuclear power source must then request launch approval from the President through the Office of Science and Technology Policy. The ultimate authority for launch and use of the nuclear power source lies with the President of the United States.

Figure 35 shows the generalized sequence of events in this flight safety evaluation process. Because safety features are designed into U.S. nuclear power sources from the very beginning, this safety review process is actually an integral part of the overall flight system development.

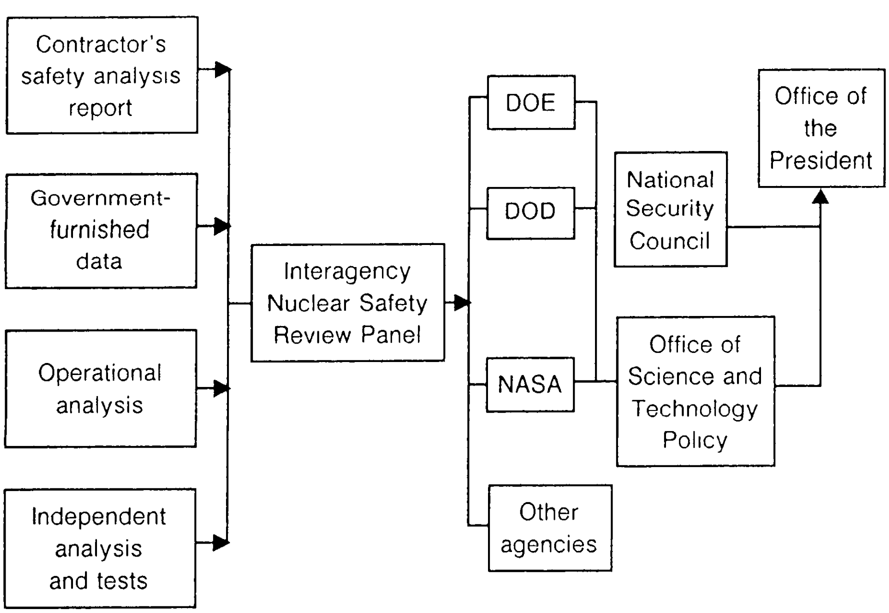


Figure 35

U.S. Safety Review and Launch Approval Process

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Thermal Management in Space

Abe Hertzberg

The vehicles and habitats associated with space industrialization and the exploitation of nonterrestrial resources will inevitably require energy systems far exceeding the current requirements of scientific and exploratory missions. Because of the extended duration of these missions, it is not possible to consider systems involving expendables such as non-regeneratable fuel cells. Therefore, these missions become hostages to the capability of continuous-power energy systems. These systems will need to provide hundreds of kilowatts to tens of megawatts of electrical power to a product fabrication system, whether it uses terrestrial or nonterrestrial raw materials.

Because the power system will be located in an essentially airless environment, rejecting waste heat becomes a limiting aspect of it. In the following paragraphs, I will review space-based or asteroidal and lunar based power generating systems, as well as the capability of existing technologies to dissipate this heat into the airless environment of space.

It should be pointed out that in a vacuum environment, convection is no longer available and the only mechanism of rejecting heat is radiation. Radiation follows the Stefan-Boltzmann Law

$$E = \sigma T^4$$

where

E = the energy rejected

σ, the Stefan-Boltzmann constant, = 5.67 W m^{-2} K^{-4}

T = the temperature at which the heat is radiated

That is, the total amount of heat radiated is proportional to the surface area of the radiator. And the lower the radiation temperature, the larger the radiator area (and thus the radiator mass, for a given design) must be.

The radiator can only reject heat when the temperature is higher than that of the environment. In space, the optimum radiation efficiency is gained by aiming the radiator at free space. Radiating toward an illuminated surface is less effective, and the radiator must be shielded from direct sunlight.

The rejection of heat at low temperatures, such as would be the case in environmental control and in the thermal management of a materials processing unit, is particularly difficult. Therefore, the design and operation of the heat rejection system is crucial for an efficient space-based energy system.

Space-Based Power Generating Systems

In a previous paper, space-based power generating systems have been described in detail. Solar photovoltaic systems have a generating capability of up to several hundred kilowatts. The power output range of solar thermal systems is expected to be one hundred to perhaps several hundred kilowatts. While in principle these power systems can be expanded into the megawatt region, the prohibitive demands for collection area and lift capacity would appear to rule out such expansion. Megawatt and multimegawatt nuclear power reactors adapted for the space environment appear to offer a logical alternative. In this paper, I deal only with the burdens these three types of power system will place on the heat management system.

Solar photovoltaics themselves will not burden the power generating system with a direct heat rejection requirement, since the low energy density of the system requires such a great collection area that it allows rejection of waste radiant energy. However, if these systems are to be employed in low Earth orbit or on a nonterrestrial surface, then a large amount of energy storage equipment will be required to ensure a continuous supply of power (as the devices do not collect energy at night). And the round-trip inefficiencies of even the best energy storage system today will require that a large fraction—perhaps 25 percent—of the electrical power generated must be dissipated as waste heat and at low temperatures.

Solar thermal systems, which include a solar concentrator and a dynamic energy conversion system, are presumed to operate at relatively high temperatures (between 1000 and 2000 K). The efficiencies of the energy conversion system will lie in the range of 15 to perhaps 30 percent. Therefore we must consider rejecting between 70 and 85 percent of the energy collected. In general, the lower the thermal efficiency, the higher the rejection temperature and the smaller the radiating area required. As with solar photovoltaic systems, the inefficiencies of the energy storage system will have to be faced by the heat rejection system, unless high temperature thermal storage is elected.

The current concepts for nuclear power generating systems involve reactors working with relatively low-efficiency energy conversion systems which reject virtually all of the usable heat of the reactor but at a relatively high temperature. Despite the burdens that this low efficiency places on nuclear fuel use, the energy density of nuclear systems is so high that the fuel use factor is not expected to be significant.

In all of these systems the output power used by the production system in environmental control and manufacturing (except for a small fraction which might be stored as endothermic heat in the manufactured product) will have to be rejected at temperatures approaching 300 K.

I think it fair to state that, in many of the sketches of space industrial plants I have seen, the power system is little more than a cartoon because it lacks sufficient detail to address the problem of thermal management. We must learn to maintain an acceptable thermal environment, because it is expected to become a dominant engineering consideration in a complex factory and habitat infrastructure.

As an example of the severity of this problem, let us examine the case of a simple nuclear power plant whose energy conversion efficiency from thermal to electric is approximately 10 percent. The plant is to generate 100 kW of useful electricity. The reactor operates at approximately 800 K, and a radiator with emissivity equal to 0.85 would weigh about 10 kg/m^2. The thermal power to be dissipated from the reactor would be about 1 MW. From the Stefan-Boltzmann Law, the area of the radiator would be about 50 m^2 and the mass approximately 500 kg. This seems quite reasonable.

However, we must assume that the electricity generated by the power plant, which goes into life support systems and small-scale manufacturing, would eventually have to be dissipated also, but at a much lower temperature (around 300 K). Assuming an even better, aluminum radiator of about 5 kg/m^2, with again an emissivity of 0.85, in this case we find that the area of the low temperature heat rejection component is 256 m^2, with a mass approaching 1300 kg.* Therefore, we can see that the dominant heat rejection problem is not that of the primary power plant but that of the energy that is used in life support and manufacturing, which must be rejected at low temperatures. Using the waste heat from the nuclear power plant for processing may be effective. But, ironically, doing so will in turn require more radiator surface to radiate the lower temperature waste heat.

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*Using the Stefan-Boltzmann Law,

$$
\begin{aligned}
E_1 &= 5.67 \times 10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}}\ (800\ \mathrm{K})^4 \\
&= 5\ 67 \times 10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}} \times 4096 \times 10^8\ \mathrm{K}^4 \\
&= 5\ 67\ \mathrm{W\ m^{-2}} \times 4\ 10 \times 10^3 \\
E_1 &= 23.3\ \mathrm{kW\ m^{-2}}
\end{aligned}
$$

900 kW $\div$ 23.3 kW m^{-2} = 38 6 m^2
and 38 6 m^2 $\div$ 0 85 = 45 4 m^2

$$
\begin{aligned}
E_2 &= 5.67 \times 10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}}\ (300\ \mathrm{K})^4 \\
&= 5.67 \times 10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}} \times 81 \times 10^8\ \mathrm{K}^4 \\
&= 5.67\ \mathrm{W\ m^{-2}} \times 81 \\
E_2 &= 459\ \mathrm{W\ m^{-2}}
\end{aligned}
$$

100 kW $\div$ 459 W m^{-2} = 0 2179 x 10^3 m^2 = 218 m^2
and 218 m^2 $\div$ 0.85 = 256 m^2

Heat Rejection Systems

In this section I will deal with systems designed to meet the heat rejection requirements of power generation and utilization. These heat rejection systems may be broadly classified as passive or active, armored or unarmored. Each is expected to play a role in future space systems.

Heat pipes: The first of these, called the "heat pipe," is conventionally considered the base system against which all others are judged. It has the significant advantage of being completely passive, with no moving parts, which makes it exceptionally suitable for use in the space environment.

For the convenience of the reader, I will briefly describe the operational mechanism of the basic heat pipe. (See figure 36.) The heat pipe is a thin, hollow tube filled with a fluid specific to the temperature range at which it is to operate. At the hot end, the fluid is in the vapor phase and attempts to fill the tube, passing through the tube toward the cold end, where it gradually condenses into the liquid phase. The walls of the tube, or appropriate channels grooved into the tube, are filled with a wick-like material which returns the fluid by surface tension to the hot end, where it is revaporized and recirculated.

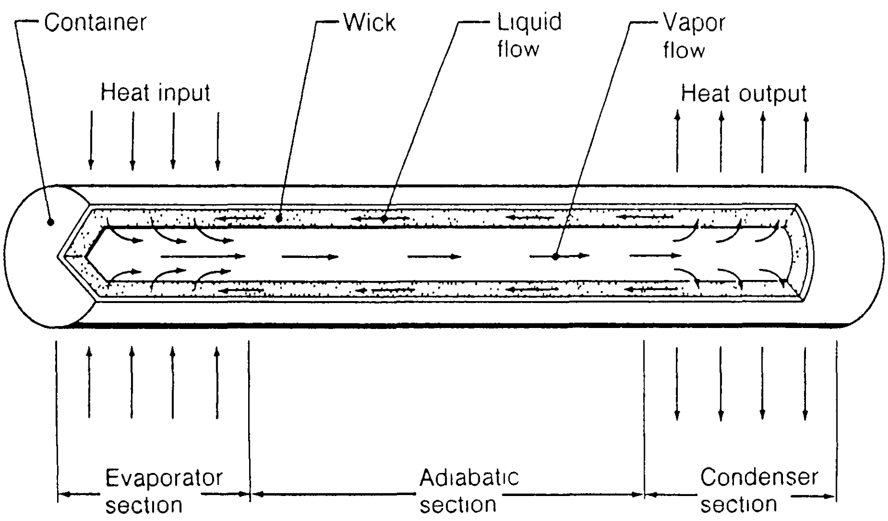


Figure 36

Components and Principle of Operation of a Conventional Heat Pipe

A conventional heat pipe consists of a sealed container with a working fluid, a passageway for vapor, and a capillary wick for liquid transport. During operation, the heat pipe is exposed to external heat at one end (the evaporator section). This heat causes the working fluid in the capillary wick to vaporize, removing heat equal to the heat of vaporization of the fluid. The vapor is forced down the center of the pipe by pressure from the newly forming vapor. When the vapor reaches the cool end of the pipe (the condenser section), it condenses to a liquid. The liquid soaks into the capillary wick, through which it travels back to the evaporator section. As the fluid condenses, it gives up the heat of vaporization, which is then conducted outside the end of the pipe.

Essentially the system is a small vapor cycle which uses the temperature difference between the hot and cold ends of the tube as a pump to transport heat, taking full advantage of the heat of vaporization of the particular fluid.

The fluid must be carefully selected to match the temperature range of operation. For example, at very high temperatures a metallic substance with a relatively high vaporization temperature, such as sodium or potassium, may be used. However, this choice puts a constraint on the low temperature end since, if the fluid freezes into a solid at the low temperature end, operation would cease until the relatively inefficient conduction of heat along the walls could melt it. At low temperatures a fluid with a low vaporization temperature, such as ammonia, might well be used, with similar constraints. The temperature may not be so high as to dissociate the ammonia at the hot end or so low as to freeze the ammonia at the cold end.

With proper design, heat pipes are an appropriate and convenient tool for thermal management in space systems. For example, at modest temperatures, the heat pipe could be made of aluminum, because of its relatively low density and high strength. Fins could be added to the heat pipe to increase its heat dissipation area. The aluminum, in order to be useful, must be thin enough to reduce the mass carried into space yet thick enough to offer reasonable resistance to meteoroid strikes.

A very carefully designed solid surface radiator made out of aluminum has the following capabilities in principle: The mass is approximately 5 kg/m^2 with an emissivity of 0.85; the usable temperature range is limited by the softening point of aluminum (about 700 K). At higher temperatures, where refractory metals are needed, it would be necessary to multiply the mass of the radiator per square meter by at least a factor of 3. Nevertheless, from 700 K up to perhaps 900 K, the heat pipe radiator is still a very efficient method of rejecting heat.

A further advantage is that each heat pipe unit is a self-contained machine. Thus, the puncture of one unit does not constitute a single-point failure that would affect the performance of the whole system. Failures tend to be slow and graceful, provided sufficient redundancy.

Pump loop system: The pump loop system has many of the same advantages and is bounded by many of the same limitations associated with the heat pipe radiator. Here heat is collected through a system of fluid loops and pumped into a radiator system similar to conventional radiators used on Earth. It should be pointed out that in the Earth environment the radiator actually radiates very little heat; it is designed to convect its heat. The best known examples of the pump loop system currently used in space are the heat rejection radiators used in the Shuttle. These are the inner structure of the clamshell doors which are deployed when the doors are opened (fig. 37).

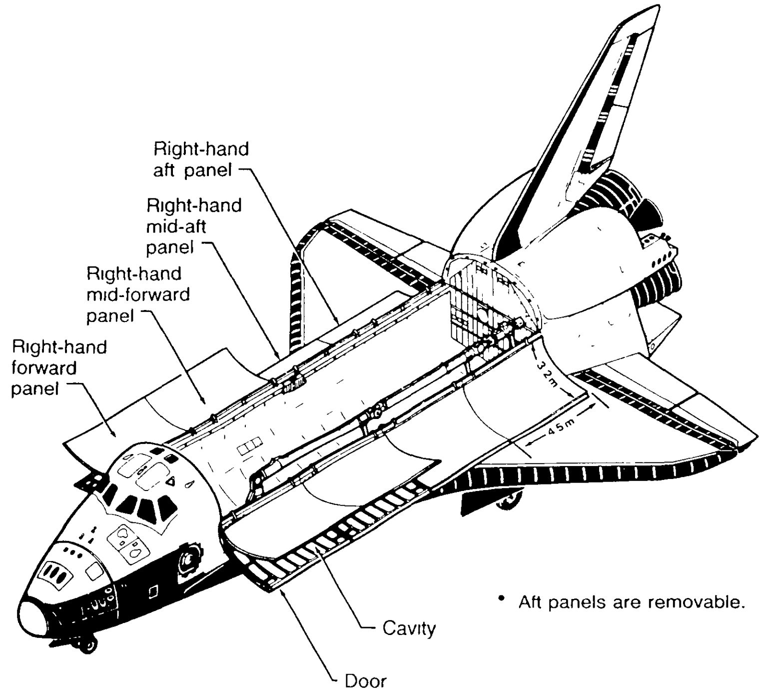
Pump loop systems have a unique advantage in that the thermal control system can easily be integrated into a spacecraft or space factory. The heat is picked up by conventional heat exchangers within the spacecraft, the carrier fluid is pumped through a complex system of pipes (extended by fins when deemed effective), and finally the carrier is returned in liquid phase through the spacecraft. In the case of the Shuttle, where the missions are short, additional thermal control is obtained by deliberately dumping fluid.

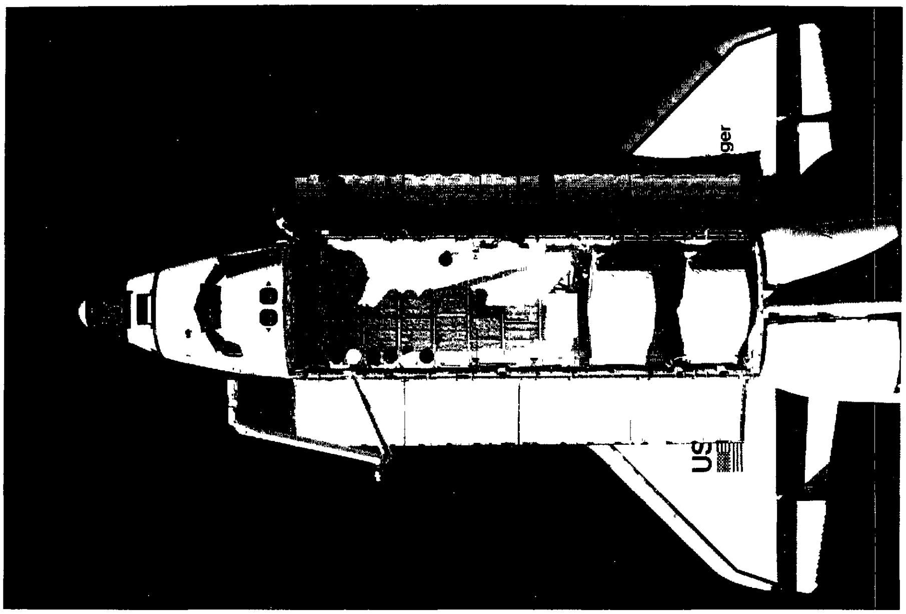
Since the system is designed to operate at low temperatures, a low density fluid, such as ammonia, may on occasion, depending on heat loading, undergo a phase change. Boiling heat transfer in a low gravity environment is a complex phenomenon, which is not well understood at the present time. Because the system is subjected to meteoroid impact, the basic primary pump loops must be strongly protected.

Figure 37

Pump Loop Radiators on the Space Shuttle Payload Bay Doors

a. The space radiators, which consist of two deployable and two fixed panels on each payload bay door, are designed to reject waste heat during ascent (doors closed) and in orbit (doors open). Each panel contains parallel tubes through which the Freon in the heat loops can pass, bringing waste heat from other parts of the orbiter. The total length of Freon tubing in these panels is 1.5 km.





b. The panels have a heat rejection capacity of 5480 kJ/hr (5400 Btu/hr) during ascent through the atmosphere with the doors closed and 23 kJ/hr (21.5 Btu/hr) during orbital operations with the doors open.

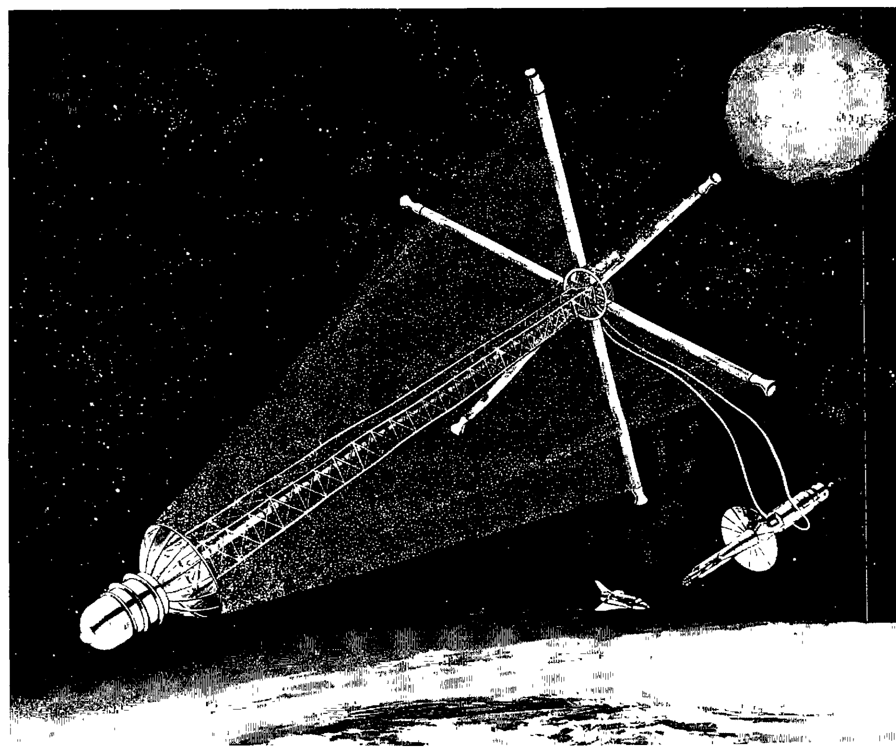
Despite these drawbacks, pump loop systems will probably be used in conjunction with heat pipe systems as thermal control engineers create a viable space environment. These armored (closed) systems are rather highly developed and amenable to engineering analysis. They have already found application on Earth and in space. A strong technology base has been built up, and there exists a rich literature for the scientist-engineer to draw on in deriving new concepts.

Advanced Radiator Concepts

The very nature of the problems just discussed has led to increased efforts on the part of the thermal management community to examine innovative approaches which offer the potential of increased performance and, in many cases, relative invulnerability to meteoroid strikes. Although I cannot discuss all of these new approaches, I will briefly describe some of the approaches under study as examples of the direction of current thinking.

Improved conventional approaches: The continuing search for ways to improve the performance of heat pipes has already shown that significant improvements in the heat pumping capacity of the heat pipe can be made by clever modifications to the return wick loop. Looking further downline at the problem of deployability, people are exploring flexible heat pipes and using innovative thinking. For example, a recent design has the heat pipes collapsing into a sheet as they are rolled up, the same way a toothpaste tube does. Thus, the whole ensemble may be rolled up into a relatively tight bundle for storing and deploying. However, because the thin-walled pipes are relatively fragile and easily punctured by meteoroids, more redundancy must be provided. The same principles, of course, can be applied to a pump loop system and may be of particular importance when storage limits must be considered. These are only examples of the various approaches taken, and we may confidently expect a steady improvement in the capability of conventional thermal management systems.

The liquid droplet radiator: The basic concept of the liquid droplet radiator is to replace a solid surface radiator by a controlled stream of droplets. The droplets are sprayed across a region in which they radiate their heat; then they are recycled to the hotter part of the system. (See figure 38.)



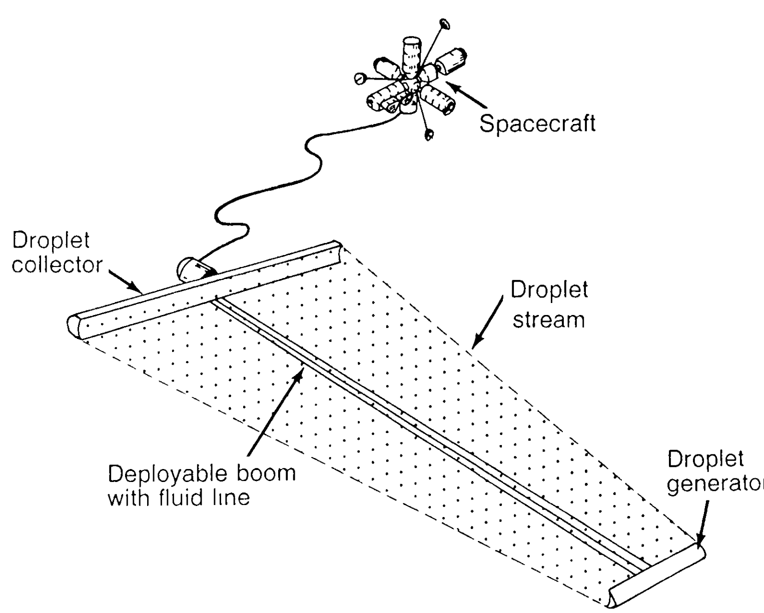


Figure 38

Two Concepts for a Liquid Droplet Radiator

In one concept (top), droplets are generated at the base of a cone which contains the source of the waste heat (a nuclear reactor, for example), and the molten droplets are sprayed to a six-armed collector array, where they are caught and then pumped back through a central pipe to the reactor. In a somewhat similar concept (bottom), a deployable boom has the droplet generator at one end and the droplet collector at the other, with a fluid feed line between. Here the droplets are sprayed in a single planar pattern.

It was demonstrated some time ago that liquid droplets with very small diameters (about 100 micrometers) are easily manufactured and offer a power-to-mass advantage over solid surface radiators of between 10 and 100. In effect, large, very thin radiator sheets can be produced by the proper dispersion of the droplets. This system offers the potential of being developed into an ultralightweight radiator that, since the liquid can be stored in bulk, is also very compact.

The potential advantages of the liquid droplet radiator can be seen if we consider again the problem that was discussed at the end of the section on heat pipe radiators. We found that a very good aluminum radiator would require 256 m^2 and have a mass of nearly 1300 kg to radiate the low temperature waste heat from lunar processing. Using the properties of a liquid droplet radiator and a low density, low vapor pressure fluid such as Dow-Corning 705, a common vacuum oil, we find that, for the same area (which implies the same emissivity), the mass of the radiating fluid is only 24 kg.

Even allowing a factor of 4 for the ancillary equipment required to operate this system, the mass of the radiator is still less than 100 kg.

To achieve efficiency, the designer is required to frame the radiator in a lightweight deployable structure and to provide a means of aiming the droplets precisely so that they can be captured and returned to the system. However, present indications are that the droplet accuracies required (milliradians) are easily met by available technology. Recently, successful droplet capture in simulated 0 *g* conditions has been adequately demonstrated. An advantage of a liquid droplet radiator is that even a relatively large sheet of such droplets is essentially invulnerable to micrometeoroids, since a striking micrometeoroid can remove at most only a few drops.

The reader may be concerned that the very large surface area of the liquid will lead to immediate evaporation. However, liquids have recently been found that in the range of 300 to 900 K have a vapor pressure so low that the evaporation loss during the normal lifetime of a space system (possibly as long as 30 years) will be only a small fraction of the total mass of the radiator.

Thus, the liquid droplet radiator appears promising, particularly as a low temperature system where a large radiator is required.

Liquid droplet radiators for applications other than 0 *g* have been suggested. For example, in the lunar environment fluids with low vapor pressures can be used effectively as large area heat dissipation systems for relatively large-scale power plants. We may well imagine that such a system will take on the appearance of a decorative fountain, in which the fluid is sprayed upward and outward to cover as large an area as possible. It would be collected by a simple pool beneath and returned to the system. Such a system would be of particular advantage in the lunar environment if low mass, low vapor pressure fluids could be obtained from indigenous materials. Droplet control and aiming would no longer be as critical as in the space environment; however, the system would need to be shaded from the Sun when it is in operation.

While this system is far less developed than the systems previously discussed, its promise is so high that it warrants serious consideration for future use, particularly in response to our growing needs for improved power management.

Belt radiator concepts: The belt radiator concept is a modification of the liquid droplet concept in which an ultrathin solid surface is coated with a very low vapor pressure liquid (see fig. 39). While the surface-to-volume ratio is not limited in the same fashion as for a cylindrical heat pipe, it does not quite match that of the liquid droplet radiator. However, this system avoids the problem of droplet capture by carrying the liquid along a continuous belt by surface tension. The liquid plays a double role in this system by acting not only as the radiator but also as the thermal contact which picks up the heat directly from a heat transfer drum. Variations on this scheme, in which the belt is replaced by a thin rotating disk, are also feasible but have yet to be fully assessed.

The systems described are only indicative of the thinking which has been stimulated by the problem of thermal management. All of these systems, if developed, offer significant promise of improvement over the conventional armored systems.

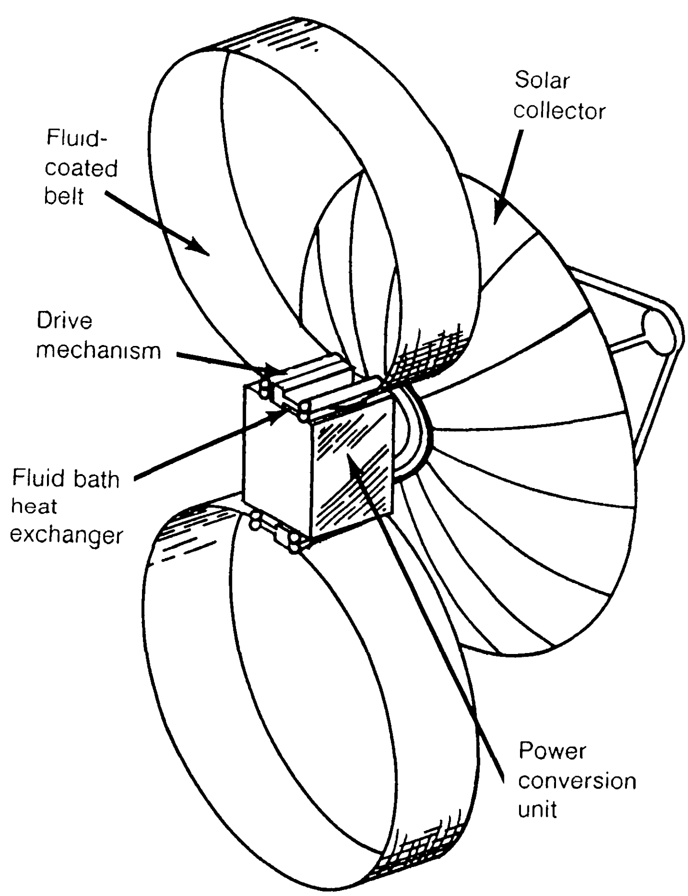


Figure 39

Belt Radiator

A related heat rejection technology is the belt radiator concept. Here the liquid is present as a thin coating on two rotating belts. As the belts rotate through the drive mechanism, they pick up hot fluid from the heat exchanger. Then, as the belts rotate through space, the fluid loses its heat. This system does not have the advantage of the high surface-area-to-mass ratio possible with a liquid droplet radiator, but it still may offer superior properties of heat transfer and damage resistance compared to solid radiators.

Laser Power Transmission

Edmund J. Conway

Since their development, lasers have offered the potential of projecting large amounts of power onto a distant, small area. (Laser power was once measured in "gillettes," the thickness in number of razor blades it took to just stop the beam.) Initially, this characteristic seemed good for weapons (e.g., the laser rifle) and mining (thermal fracture or vaporization of rock). Actual applications later developed in the areas of cutting (anything from sheet metal to cloth), welding, scribing, and surgery.

One of the earliest proposals for the application of a high-powered laser in the civilian space program was made by Kantrowitz (1972). He proposed an Earth-to-orbit launch system in which a laser on the ground supplied thermal energy to a single species of rocket propellant (such as hydrogen). The removal of the oxidizer, no longer needed to release chemical energy for propulsion, reduced the lift-off weight of Earth-launched vehicles.

This and similar proposals on power and propulsion generated a great deal of speculation and study in the 1970s. These activities, although generally incomplete and sometimes contradictory, identified several themes:

- Lower cost power and propulsion is key to the development of near-Earth space.
- Solar- and nuclear-powered lasers have the characteristics for high payoff in space applications.
- Expensive transportation applications show high potential for cost reduction through the use of remote laser power.
- Economical power beaming in space requires multiple customers who cannot use available (solar photovoltaic) power sources.
- High laser conversion efficiency is a key power-beaming challenge.
- NASA laser power requirements are very different from those of DOD and DOE, but NASA can benefit from the breadth of basic research generated by the programs of other agencies.

A particularly complete study by Holloway and Garrett (1981) showed substantial payoff for both laser-thermal- and laser-electric-powered orbit transfer vehicles. A recent comparison by DeYoung and coworkers (1983) suggests that with a laser providing 100 kW or more of power for electric propulsion and for other onboard utility needs, spacecraft will be able to operate in low altitude, high drag orbits and will be much lighter and smaller.

From the studies, then, a general set of requirements are emerging for beaming power by laser to currently envisioned space missions. First, the laser must be capable of long-term continuous operation without significant maintenance or resupply. For this reason, solar- and nuclear-powered lasers are favored. Second, the laser must supply high average power, on the order of 100 kW or greater for applications studied so far. For this reason, continuous wave or rapidly pulsed lasers are required.

Since solar energy is the most available and reliable power source in space, recent research designed to explore the feasibility of laser power transmission between spacecraft in space has focused on solar-pumped lasers. Three general laser mechanisms have been identified:

- Photodissociation lasing driven directly by sunlight
- Photoexcitation lasing driven directly by sunlight
- Photoexcitation lasing driven by thermal radiation

Solar-Pumped Photodissociation Lasers

Several direct solar lasers based on photodissociation have been identified, including six organic iodide lasants that have been successfully solar pumped and emit at the iodine laser wavelength of 1.3 micrometers. (See figure 40 for a possible application of such a laser.) Another lasant, IBr, has been pumped with a flashlamp and lased at 2.7 µm with a pulsed power of hundreds of watts. One organic iodide, C_3F_7I, and IBr have been investigated intensively to characterize their operation. Several reports on experimental results and modeling have been published (Zapata and DeYoung 1983, Harries and Meador 1983, Weaver and Lee 1983, Wilson et al. 1984, DeYoung 1986). An important characteristic of the photodissociation lasers under consideration is that they spontaneously recombine to form the lasant molecule again. Both C_3F_7I and IBr do this to a high degree, permitting continuous operation without resupplying lasant, as is generally required for chemical lasers. In addition, C_3F_7I absorbs almost no visible light and thus remains so cool that it may require no thermal radiator except the pipe that recirculates the lasant. A variety of other lasants offering increased efficiency are under study.

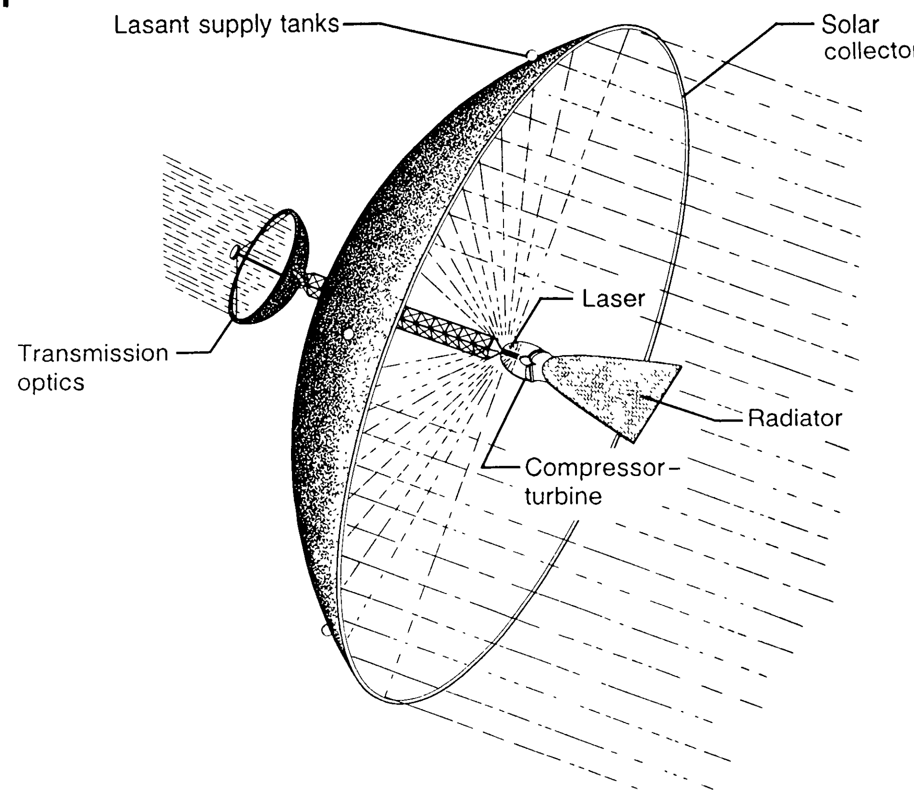


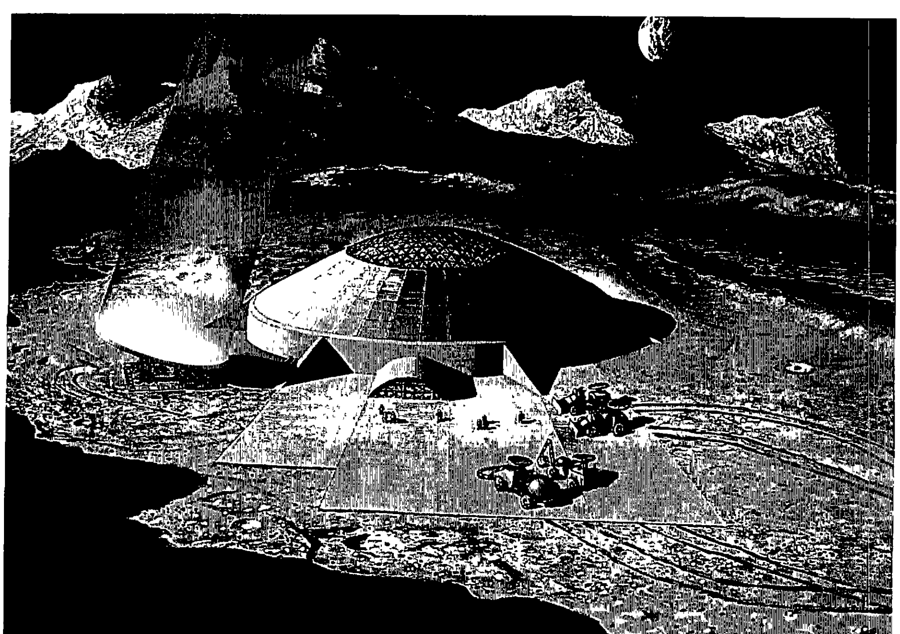
Figure 40

One-Megawatt Iodine Solar-Pumped Laser Power Station

This picture shows the elements of an orbiting laser power station. A nearly parabolic solar collector, with a radius of about 300 meters, captures sunlight and directs it, in a line focus, onto a 10-m-long laser, with an average concentration of several thousand solar constants. An organic iodide gas lasant flows through the laser, propelled by a turbine-compressor combination. The hot lasant is cooled and purified at the radiator. New lasant is added from the supply tanks to make up for the small amount of lasant lost in each pass through the laser. Power from the laser is spread and focused by a combination of transmission mirrors to provide a 1-m-diameter spot at distances up to more than 10 000 km.

Solar-Pumped Photoexcitation Lasers

Another group of direct solar-pumped lasers rely on the electronic-vibrational excitation produced by sunlight to power the laser action. Two systems are being actively studied. The first is a liquid neodymium (Nd) ion laser, which absorbs throughout the visible spectrum and emits in the near-infrared at 1.06 µm. This lasant has lased with flashlamp pumping and is currently being tried with solar pumping, since calculations indicate feasibility. A second candidate of this sort is a dye laser, which absorbs in the blue-green range and emits in the red, near 0.6 µm. These lasers offer good quantum efficiency and emission that is both of short wavelength and tunable. However, the lasers require extremely high excitation to overcome their high threshold for lasing, and the feasibility of achieving this with concentrated sunlight is still a question for further research.



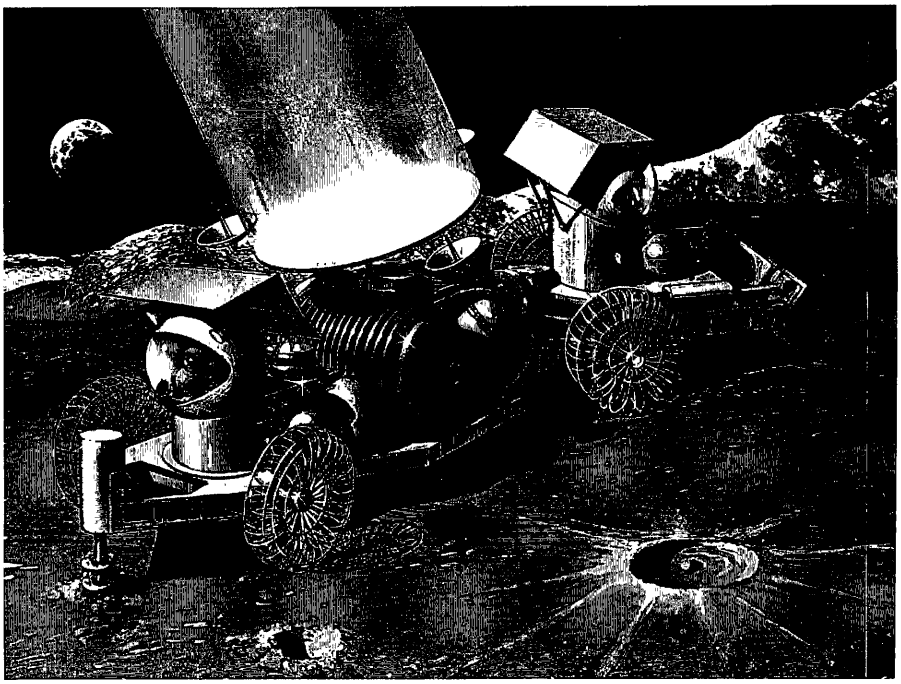
Laser Power to a Lunar Base

In this artist's concept, a large receiver is covered with photovoltaic converters tuned to the laser wavelength. Such a system could produce electric power with an efficiency near 50 percent.

Artist: Bobby E. Silverthorn

Indirect Photoexcitation Lasers

Photoexcitation lasers driven by thermal radiation produced by the Sun are termed indirect solar-pumped lasers. The lower pumping energy implies longer wavelength emission than with photodissociation lasers. Two lasers, the first blackbody-cavity-pumped laser (Insuik and Christiansen 1984) and a blackbody-pumped transfer laser (DeYoung and Higdon 1984), work on this principle. Molecules such as CO_2 and N_2O have lased with emission wavelengths between 9 µm and 11 µm. These lasers are inherently continuous wave and have generated powers approaching 1 watt in initial laboratory versions, with blackbody temperatures between 1000 K and 1500 K. While such lasers, powered by solar energy, may be used in space, they also offer great potential for converting to laser energy the thermal energy generated by chemical reactions, by nuclear power, by electrical power, or by other high-temperature sources.



Laser-Powered Lunar Prospecting Vehicle

This manned prospecting vehicle, far from the base camp, is receiving laser power for life support, electric propulsion across the lunar surface, and drilling. Since this power is available during lunar night as well as day, prospecting need not be shut down for 14 Earth days every month. A mobile habitat module (not shown) accompanies the prospecting vehicle on its traverse.

Artist: Bobby E. Silverthorn

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Conclusions

Henry W. Brandhorst, Jr.

It is abundantly clear that energy is the key to utilization of space. In fact, bold programs are completely dependent upon and in effect hostage to the availability of energy. We believe that, for either the baseline scenario or the alternative scenario that makes use of lunar resources, there is sufficient time to develop the broad mix of power sources and associated technologies necessary for success.

A list of envisioned applicable technologies related to power and energy supply for space activities at various power demand levels is shown in table 6.

In general, stepwise development of a variety of sources is envisioned: First, an expanding LEO space station with power levels up to 10 MW powered by solar or nuclear sources. Then, lightweight photovoltaic systems

TABLE 6. *Applicable Power Technologies*

Power level	Technology	Application
1 - 100 kW	Photovoltaic	Lightweight arrays for satellites in GEO Space station in LEO On the lunar surface (day only) (hardware derived from space station)
	Radioisotope	Radioisotope thermoelectric generator (RTG) for lunar rover Dynamic isotope power system (DIPS) for martian rover
	Energy storage	Individual pressure vessel (IPV) nickel-hydrogen battery Hydrogen-oxygen regenerative fuel cell (RFC) Bipolar nickel-hydrogen battery Flywheel
100 kW - 1 MW	Photovoltaic	Solar electric propulsion for orbital transfer vehicle
	Solar dynamic	Space station in LEO On the lunar surface (day only) (hardware derived from space station)
	Direct solar heat	Mirrors and lenses for processing lunar and asteroidal materials
	Nuclear	SP-100 (safe, human-rated derivative) for lunar base
	Waste heat rejection	Liquid droplet radiator Belt radiator Rollup heat pipes
1 - 10 MW	Nuclear	Nuclear electric propulsion for orbital transfer vehicle or piloted spacecraft to Mars
	Waste heat rejection	Liquid droplet radiator Belt radiator Rollup heat pipes
	Power management	High-voltage transmission and distribution Laser power beaming

for GEO and lunar surface operation. It is likely that lunar camps staffed only during the day could derive all their power (25-100 kW) from solar arrays. Lightweight electrochemical storage systems such as hydrogen-oxygen regenerative fuel cells would find use at GEO and, in concert with solar arrays, would power surface-roving vehicles and machines.

When full-time staffing becomes appropriate, we believe that nuclear systems are the most likely source of power. Power levels in the 100-1000 kW range would be derived from lunar-modified SP-100-class designs, while powers in the 1-10 MW range would be derivatives of civil and military multimegawatt nuclear developments. These man-rated, safe nuclear systems would simply be used as power demands warranted.

Thus, for a lunar base, photovoltaic (or solar dynamic) systems would be used initially for daytime operation, SP-100-class systems would be used for full-time staffing at power levels to 1 MW (by replication or design), and these would be followed by multimegawatt systems for the 1-10 MW needs. Similar progress is envisioned for either scenario for GEO operations and asteroid and Mars exploration. Attention must also be paid to the impact of the lunar, asteroidal, or martian environment on parameters of the power system.

We consider it unlikely that use of nonterrestrial resources will affect power system development before 2010. It is rather the opposite: power systems will enable the development and use of nonterrestrial resources.

Significant advances in the areas of nuclear power development and beamed power transmission will be made by both the military and the civilian space program. Full advantage must be taken of such corollary developments.

It should be noted that development of the 1- to 10-MW class of nuclear (or even solar) power systems will have a profound influence on the state and direction of the electric propulsion programs. These power levels enable electrically propelled orbital transfer vehicles and interplanetary explorers to travel to the outermost fringes of the solar system with larger payloads and shorter trip times than chemical systems. In view of these potentialities, a strong emphasis on developing such propulsion systems is warranted.

Assuming that current programs in photovoltaics and in the SP-100 nuclear plant continue, the following are considered critical technological issues for further research and development. They are presented in order of priority. By piggybacking atop and augmenting existing programs, we can ensure timely development of the requisite systems.

1. SP-100-derivative nuclear power system capable of providing power to 1 MW in an environment safe for humans

2. Large-scale photovoltaic arrays; solar dynamic power conversion suitable for space, using collectors that concentrate sunlight

3. Solar furnaces and process heat applications suitable for processing space resources at high temperatures

4. Multimegawatt (1-10 MW) nuclear power-generating systems for electricity and heat

5. Thermal rejection systems to reject waste heat from the power conversion system, processing, and environmental conditioning (New concepts for efficient radiation are required; the use of lunar subsurface rejection should be investigated.)

6. High-voltage electric transmission and distribution of multimegawatt power

7. Thermal energy control and distribution for both manned and unmanned systems

8. Lightweight, rechargeable thermal and electrical storage

9. Machine design including human factors; robotics to substitute for humans in hostile environments

10. Laser technology for solar and infrared sources to beam power in space

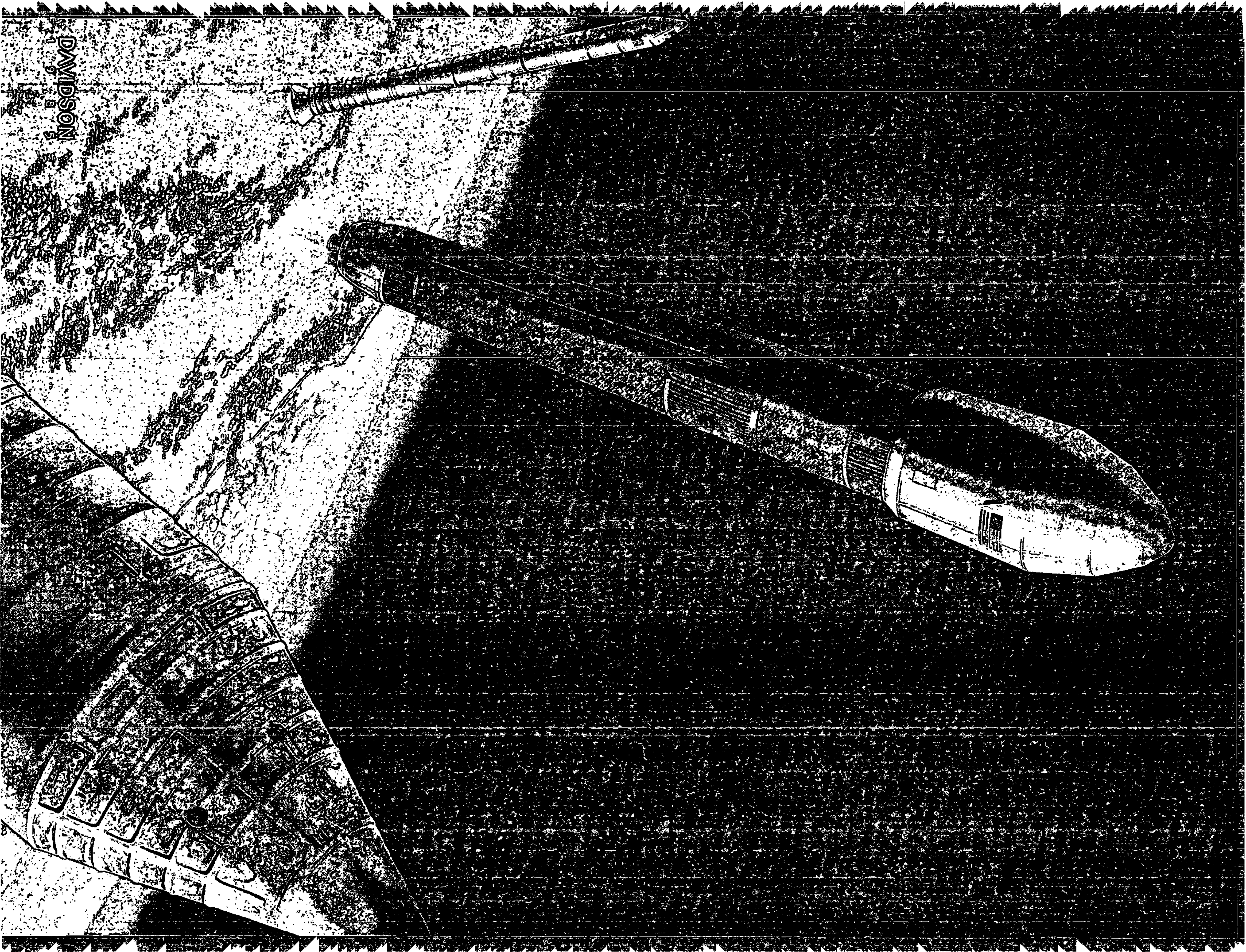
11. Environmental interactions in space associated with energy sources, processing, and work in space; i.e., the impact of foreign materials and pollutants

A broadly based program aimed at developing solar and nuclear power systems to the multimegawatt level is of the highest priority. For brevity's sake, we have discussed only a few of the variety of long-range, innovative energy-related programs supported by NASA, DOD, DOE, and industry. To ensure a broadly based, innovative program, a portion (up to 5%) of the funds allocated for space power research should be devoted to areas that may permit radical advance and extremely high payoff, albeit at high risk.

Heavy Lift Launch Vehicle

An unmanned heavy lift launch vehicle derived from the Space Shuttle to lower the cost of transporting material to Earth orbit would make it feasible to transport to orbit elements of a lunar base or a manned spacecraft destined for Mars. Its first stage would be powered by two solid rocket boosters, shown here after separation. Its second stage would be powered by an engine cluster at the aft end of the fuel tank that forms the central portion of the vehicle. All this pushes the payload module located at the forward end. This payload module can carry payloads up to 30 feet (9.1 meters) in diameter and 60 feet (18.3 meters) in length and up to 5 times as heavy as those carried by the Shuttle orbiter.

Artist: Dennis Davidson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Transport: Introduction

William Lewis and Sanders D. Rosenberg

The propulsion workshop addressed the current status and future requirements for space propulsion by considering the demand for transportation in the three scenarios defined by workshop 1. The low-growth scenario assumes no utilization of nonterrestrial resources; the two more aggressive scenarios include the use of nonterrestrial resources, particularly propellants. The scenarios using nonterrestrial resources demand that tens of thousands of tons of rockets, propellants, and payloads be shipped through cislunar space by 2010. Propellant oxygen derived from the Moon is provided in the second scenario, and propellants from asteroids or the Mars system are provided in the third. The scenario using resources derived only from the Earth demands much less shipping of hardware but much more shipping of propellants.

We included in our examination a range of technologies that could be developed to meet the transportation requirements of these scenarios. Descriptions of these technologies can be found in the individual contributions that follow this introduction.

It appears that current oxygen-hydrogen propulsion technology is capable of meeting the transportation requirements of all scenarios. But, if this technology is used in conjunction with advanced propulsion technology, a much more efficient space transportation system can be developed. Oxygen from the Moon promises to significantly reduce the yearly tonnage on the transport leg from the Earth to low Earth orbit (LEO). Hydrogen from Earth-crossing asteroids or from lunar volatiles (in cold-trapped ices or the lunar regolith) would offer further improvement and reduce propulsion technology challenges. Mars missions are supportable by propellants derived in the Mars system, probably from Phobos. Unfortunately, these opportunities cannot be taken at current funding levels.

The NASA baseline scenario is shown in figure 1. This scenario assumes the development of a space transportation network without utilization of nonterrestrial resources. The space station is developed first and used to support development in geosynchronous Earth orbit (GEO), manned exploration of the Moon, and unmanned exploration of the solar system. Beyond the timeframe considered, the space station can serve as a base for lunar settlement and manned Mars exploration.

The nonterrestrial resource scenarios, figures 2 and 3, initially follow almost the same path but, after the space station is established, move less toward GEO and more toward the Moon. In addition, these scenarios consider selective mining of asteroids that cross the Earth's orbit. Nonterrestrial resources are used to reduce transportation and construction costs for projects in cislunar space. Eventually, the space station and lunar base serve as production and staging areas for manned Mars exploration.

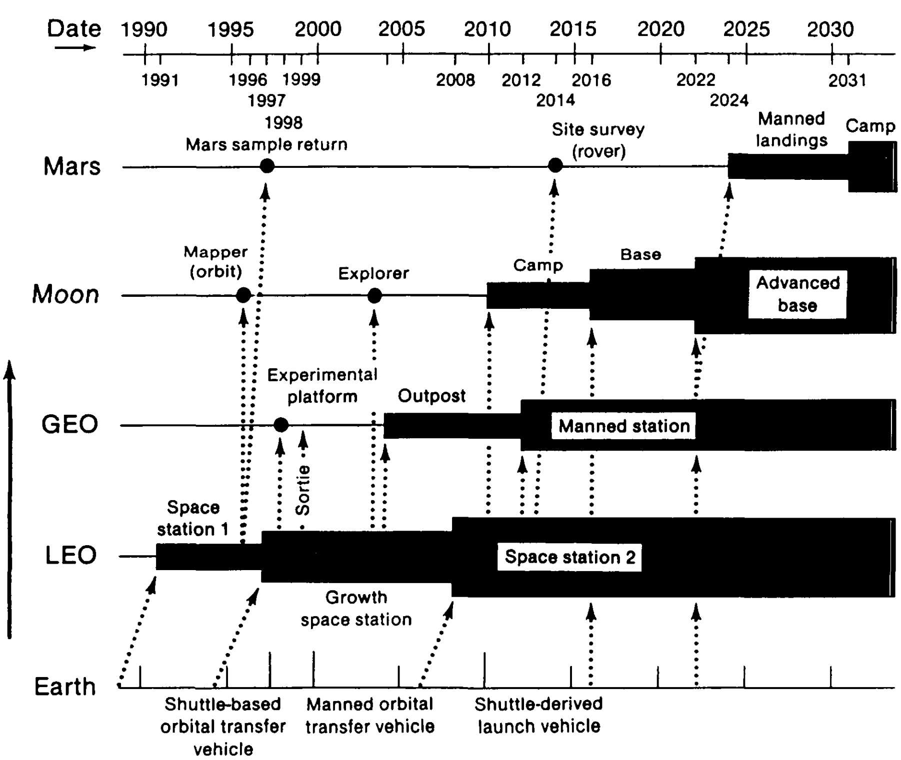


Figure 1

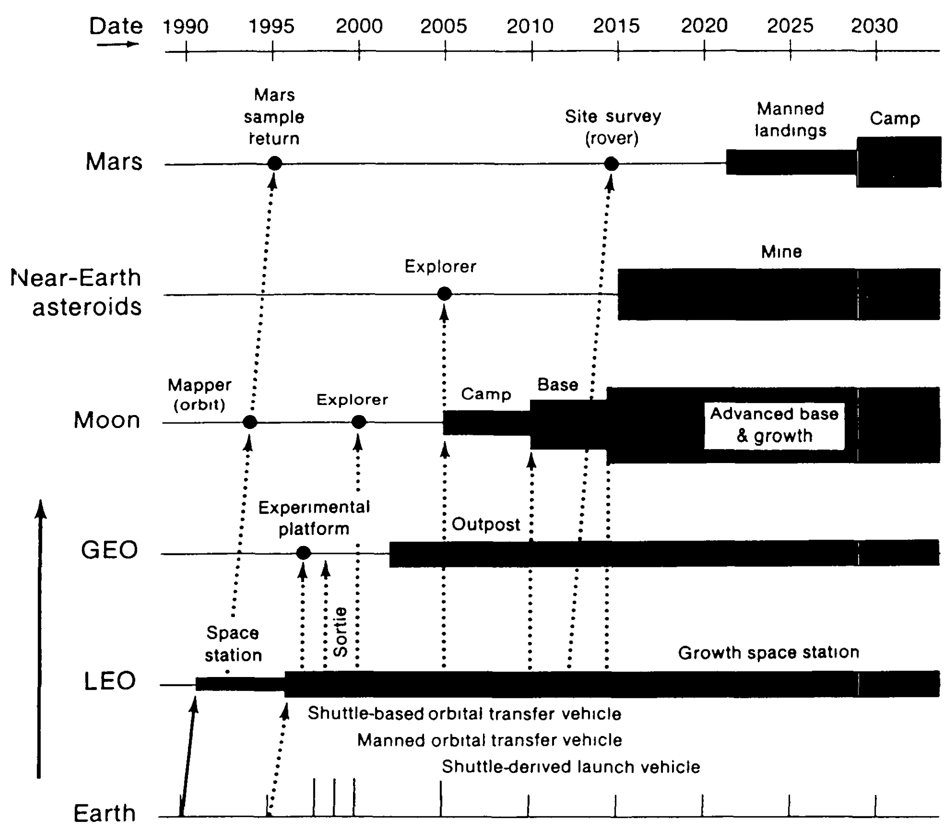
Baseline Scenario

If NASA continues its business as usual without a major increase in its budget and without using nonterrestrial resources as it expands into space, this is the development that might be expected in the next 25 to 50 years. The plan shows an orderly progression in manned missions from the initial space station in low Earth orbit (LEO) expected in the 1990s, through an outpost and an eventual space station in geosynchronous Earth orbit (GEO) (from 2004 to 2012), to a small lunar base in 2016, and eventually to a Mars landing in 2024. Unmanned precursor missions would include an experiment platform in GEO, lunar mapping and exploration by robot, a Mars sample return, and an automated site survey on Mars. This plan can be used as a baseline scenario against which other, more ambitious plans can be compared.

Figure 2

Scenario for Space Resource Utilization

Space resource utilization, a feature lacking in the baseline plan, is emphasized in this plan for space activities in the same 1990-2035 timeframe. As in the baseline scenario, a space station in low Earth orbit (LEO) is established in the early 1990s. This space station plays a major role in staging advanced missions to the Moon, beginning about 2005, and in exploring near-Earth asteroids, beginning about the same time. These exploration activities lead to the establishment of a lunar camp and base which produce oxygen and possibly hydrogen for rocket propellant. Automated missions to near-Earth asteroids begin mining these bodies by about 2015, producing water and metals which are returned to geosynchronous Earth orbit (GEO), LEO, lunar orbit, and the lunar surface. Oxygen, hydrogen, and metals derived from the Moon and the near-Earth asteroids are then used to fuel space operations in Earth-Moon space and to build additional space platforms and stations and lunar base facilities. These space resources are also used as fuel and materials for manned Mars missions beginning in 2021. This scenario might initially cost more than the baseline scenario because it takes large investments to put together the facilities necessary to extract and refine space resources. However, this plan has the potential to significantly lower the cost of space operations in the long run by providing from space much of the mass needed for space operations.



Transportation System Requirements

Table 1 lists the principal routes between nodal points in the Earth-Moon-asteroid-Mars system and identifies technologies for each of the legs. The principal distinctions between categories of space propulsion are related to whether significant gravitational fields are involved. Leaving a gravitational field requires a high-thrust propulsive system. Orbit-to-orbit trips can be made with fairly low thrust, though such trips take longer and are less efficient because gravity reduces effective thrust. If a planet has an atmosphere, atmospheric drag (aerobraking) can be used to offset requirements for inbound propulsion. Because of differences in mission duration and in the accelerations achievable using various techniques, some transportation modes are more relevant to manned flights and others to cargo flights. Manned flights require fast and safe transportation to minimize life support requirements and radiation exposure. Cargo flights can be slower, less reliable, and thus cheaper. We also discussed to a limited extent transportation on the surface of the Moon, which will require quite different technologies.

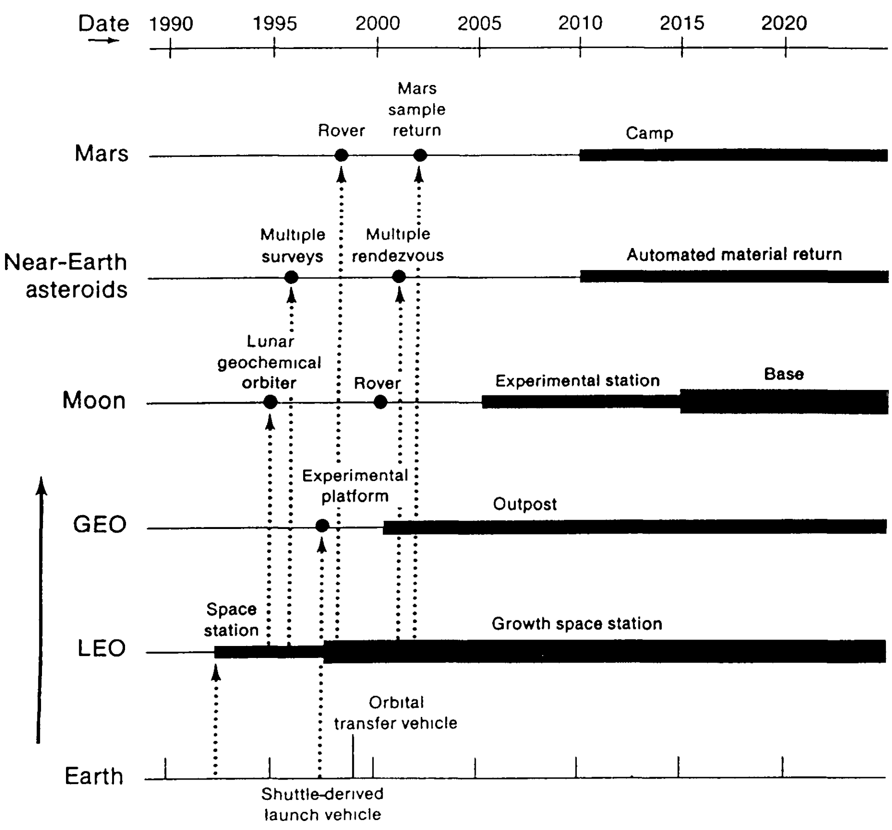


Figure 3

Scenario for Balanced Infrastructure Buildup

In this scenario, each location in space receives attention in a balanced approach and none is emphasized to the exclusion of others. The scenario begins with the establishment of the initial space station about 1992. This is followed by the establishment of a manned outpost in geosynchronous Earth orbit (GEO) in 2001, an experimental station on the Moon in 2006, and a manned Mars camp in 2010. In parallel with these manned activities, many automated missions are flown, including a lunar geochemical orbiter and a lunar rover, multiple surveys of near-Earth asteroids and rendezvous with them, and a martian rover and a Mars sample return. Automated mining of near-Earth asteroids beginning in 2010 is also part of this scenario.

TABLE 1. *Principal Routes Between Transportation Nodes*

(a) Nodes and their locations

Node	Location
1. Earth	Kennedy Space Center
2. Low Earth orbit (LEO)	Space station
3. Geosynchronous Earth orbit (GEO)	Shack
4. Lunar orbit	Shack
5. Moon	Advanced base
6. Earth-crossing carbonaceous chondrite asteroid	Mining base
7. Mars orbit	Shack
8. Mars	Advanced base

(b) Routes and modes of transportation for them

Leg	Transportation mode options
Earth to low Earth orbit	Chemical rockets
LEO to LEO (plane changes)	Chemical rockets Low-thrust orbital maneuvering vehicles (OMVs) Tethers
LEO to GEO, lunar orbit, asteroids, Mars orbit	Chemical-rocket-propelled orbital transfer vehicles (OTVs) Low-thrust propulsion
GEO, lunar orbit, asteroids, Mars orbit to LEO	Aerobraked chemical rockets Low-thrust propulsion
Lunar orbit to Moon	Chemical rockets Tethers
Moon to lunar orbit	Chemical rockets Electromagnetic launch Tethers
Mars orbit to Mars	Aerobraked vehicles
Mars to Mars orbit	Chemical rockets

The baseline scenario could be implemented with the Space Shuttle, Shuttle-derived launch vehicles (SDLVs), and orbital transfer vehicles (OTVs). The nonterrestrial resource scenarios require the development of additional systems. While it is technically possible to establish the transportation network for these scenarios with oxygen-hydrogen (OH) rockets alone, the expense of operating the transportation network, even for the baseline scenario, could be reduced by the introduction of non-OH rocket technologies. Let us consider briefly the technologies that could be used for three categories of transportation: surface-to-orbit, orbit-to-orbit, and surface.

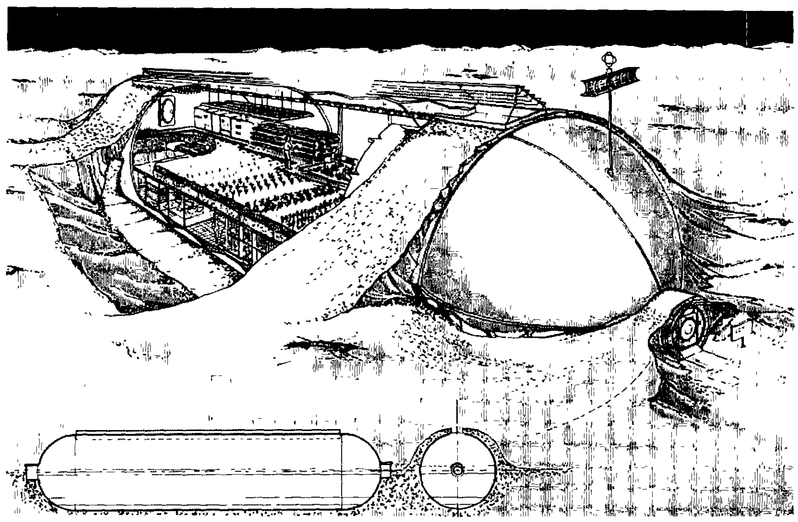
Surface-to-Orbit Transportation (Earth to Orbit, Moon to Lunar Orbit, Mars to Mars Orbit)

Transportation from the Earth's surface to orbit is conventionally accomplished using chemical rockets. There seems no readily available substitute for such rockets on this leg. Shuttle-derived launch vehicles or, if traffic becomes heavy enough, heavy lift launch vehicles (HLLVs) could provide Earth-to-orbit transportation at a lower cost than does the current Space Shuttle system. (See Salkeld and Beichel 1973, Eldred 1982 and 1984, and Davis 1983.) These systems gain efficiency by eliminating man-rated elements and reducing system weight, rather than by improving the rocket engine (although some improvements in rocket engines are still attainable). It may be worthwhile to develop such vehicles for cargo transport in the baseline scenario over the next 20 years. And the scenarios using nonterrestrial materials require such vehicles for cost-effectiveness.

Transportation from the lunar surface to orbit could be accomplished using OH rockets. The advantages of choosing OH rockets are summarized in table 2 by Sandy Rosenberg, who points out that oxygen-hydrogen propulsion is likely to persist simply because the large amount of effort that has gone into its development has led to a level of understanding which surpasses that of any alternative propulsion system. In a separate paper, Mike Simon considers the use of OH rockets in a systems sense, showing how the introduction of nonterrestrial propellants can affect the overall system performance and, eventually, reduce the cost.

TABLE 2. *Selection Basis for Oxygen-Hydrogen Propulsion*

Factor	Rationale
1. Common use of water to support human activity in space	The exploration and exploitation of space is based on a water economy because of the presence of humans. Water and oxygen are required for life support. Therefore, use of oxygen and hydrogen in propulsion systems will benefit from synergism with other parts of the space system.
2. High performance	The bipropellant combination of liquid oxygen (LO_2) and liquid hydrogen (LH_2), operating at a mixture ratio of 6:1, offers a vacuum specific impulse of 460 to 485 sec, with an environmentally acceptable exhaust. The LO_2/LH_2 bipropellant propulsion system offers a high thrust-to-weight ratio, an acceptable fraction of propellant mass to propulsion system mass, a short trip time (an important factor for all manned missions), and a firmly established technology base.

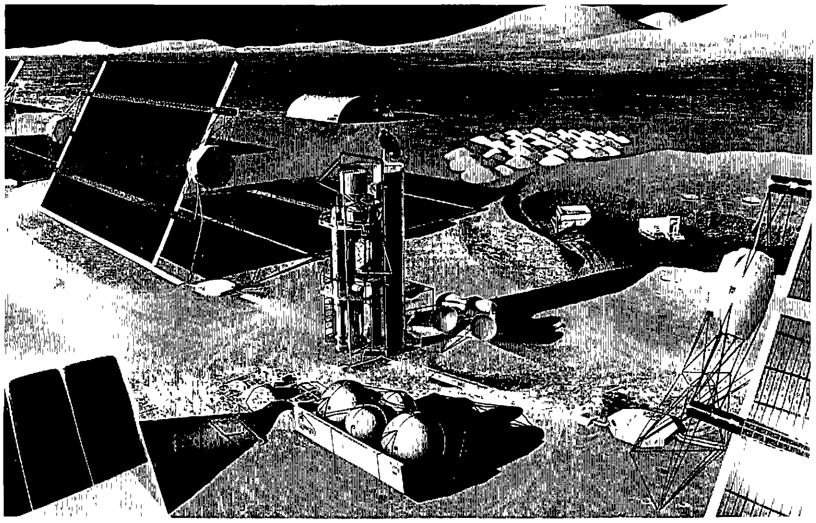


A Plant-Growing Module at a Lunar Base

Plants will require a considerable stock of water, but nearly all the water can be recycled in a properly designed controlled ecological life support system (CELSS).

TABLE 2 *(concluded)*.

Factor	Rationale
3. Technological feasibility	The technology for the long-term storage and transfer of cryogenic fluids in a low-gravity environment, which will enhance the efficient management of LO_2/LH_2 propellant, is being actively pursued by NASA's Office of Aeronautics and Space Technology (OAST). Aerobraking is also being actively studied and appears promising.
4. Benefit from nonterrestrial resources	LO_2/LH_2 propulsion benefits directly from the utilization of nonterrestrial resources; e.g., the manufacture of O_2 on the Moon and O_2 and H_2 on Mars. Earth-crossing carbonaceous asteroids may be a source of O_2 and H_2.



Oxygen Manufacturing Plant on the Moon

This plant uses a fluidized bed to reduce lunar ilmenite with hydrogen and produce water. The water is electrolyzed, the oxygen is collected, cooled, and cryogenically stored in the spherical tanks, and the hydrogen is recycled into the reactor. The plant is powered by electricity from the large solar cell arrays, each of which can generate 56 kilowatts.

Artist: Mark Dowman

Factor	Rationale
5. Programmatic support	LO_2/LH_2 propulsion gets more than 90 percent of the investment that NASA's OAST is currently making in its research program. No change in the current NASA program is required when LO_2/LH_2 propulsion is selected.

Other rocket propellants derived from nonterrestrial materials could also find use in the future. Andy Cutler considers an oxygen-hydrogen-aluminum engine as a possibility. Such an engine could use oxygen and hydrogen derived from lunar or asteroidal materials and could also provide a second use for the Space Shuttle's aluminum external tanks, which are currently thrown away.

Among the alternative technologies that may be useful are electromagnetic launchers capable of launch from the Moon to low lunar orbit and of propelling vehicles in space. The Department of Defense is funding a program of significant size in electromagnetic launch; the results of this program might be fairly cheaply adapted to the space environment. This concept is considered in a paper by Bill Snow.

Several other technologies may be of value in surface-to-orbit transportation. Tethers, in particular, can permit an orbiting station to acquire momentum from a high I_{sp} propulsion device over long periods of time and quickly transfer it to a vehicle that needs the momentum to gain orbital velocity on launch from the Moon (Carroll 1984 and 1986, Carroll and Cutler 1984). In effect, high I_{sp} is combined with high thrust, although only briefly. Andy Cutler discusses this idea.

Specific Impulse (I_{sp})

Specific impulse (I_{sp}) is a measure of the performance of a rocket engine. It is equal to the thrust generated F divided by the weight flow rate w of the propellant used:

$$I_{sp} = F / \dot{w}$$

Its units turn out to be seconds. In the English system, pounds of force (mass times acceleration or lb ft/sec²) divided by pounds of weight (mass times gravity or lb ft/sec²) per second equal seconds In the metric system, newtons (kgm/sec²) divided by kilograms (kg) times gravity (m/sec²) per second equal seconds.

Specific impulse is also equivalent to the effective exhaust velocity divided by the gravitational acceleration. This relationship can also be derived from a consideration of the units Force, or mass times acceleration, can be seen as mass per second times velocity. Weight flow rate, or mass times gravity per second, can be taken as mass per second times gravity. Thus, specific impulse equals velocity (m/sec) divided by gravity (m/sec²), or seconds again.

Orbit-to-Orbit Transportation (LEO to GEO, Lunar Orbit, Asteroids, or Mars Orbit and Back)

Orbit-to-orbit transfers within cislunar space can be handled by OH rockets. See figure 4. A series of space-based orbital maneuvering vehicles (OMVs) and orbital transfer vehicles (OTVs) is now being considered by NASA.

Aerobraking, which uses aerodynamic effects to lower orbit, may be significant in cislunar space transportation. This technology will be used primarily with high-energy systems, such as OH rockets, to slow spacecraft returning to the Earth (or entering the Mars atmosphere), reducing their need for propellant. See figure 5. This technology is under development but has not been tested in the context of GEO, lunar, asteroid, or Mars missions. No paper on aerobraking was produced during the workshop, but the principles and prospects of aerobraking have been discussed by Scott and others (1985) and Roberts (1985).

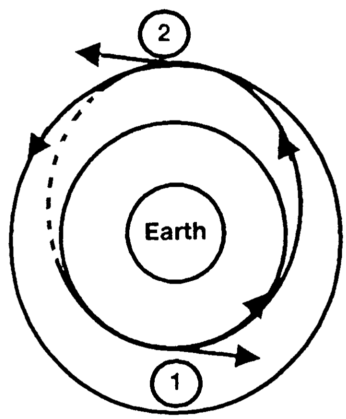


Figure 4

Orbital Transfer Maneuver

A spacecraft orbiting the Earth can raise the altitude of its orbit by firing its engines to increase its velocity in a series of two maneuvers. In the figure, the spacecraft in a low circular orbit fires its engines at point 1. Its new velocity causes an increase in orbital altitude on the opposite side of the orbit. When the spacecraft reaches the high point of this new elliptical orbit, at point 2, the engines are fired again to increase its velocity. This increase in velocity raises the low point of the elliptical orbit and in this case results in a circular orbit at a higher altitude than the original orbit. An orbit can be lowered by following this procedure in reverse.

Taken from AC Electronics Division, General Motors Corp., 1969, Introduction to Orbital Mechanics and Rendezvous Techniques, Text 2, prepared under NASA contract NAS 9-497, Nov.

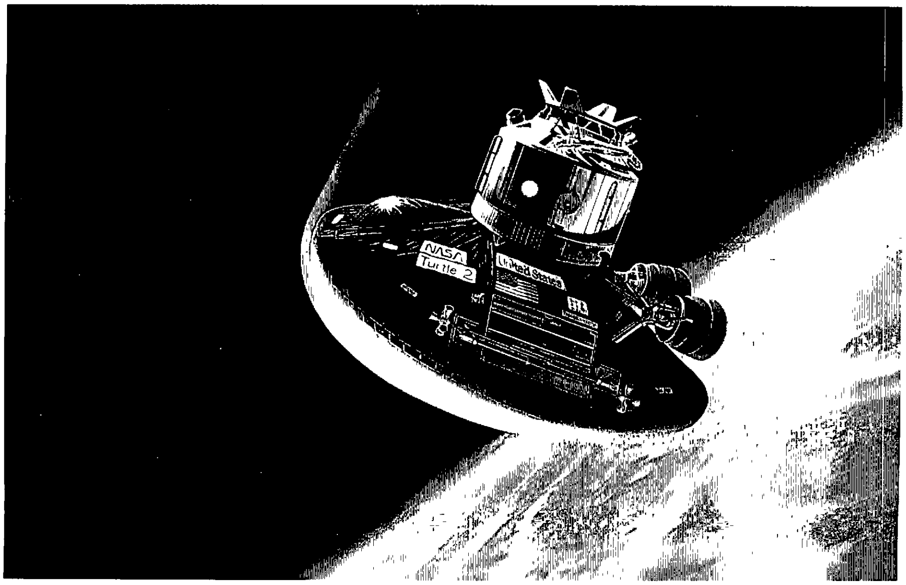


Figure 5

Aerobrake Used To Slow Down Unmanned Spacecraft Returning From Mars

Aerobrakes can reduce or eliminate the need for retrorockets because they use aerodynamic forces in the upper atmosphere of the Earth to slow down spacecraft for orbital insertion or for reentry. Aerobraking could also be used on the Mars end of a voyage to slow down spacecraft.

Artist: Pat Rawlings

Because high gravitational fields do not have to be surmounted, there are additional approaches to orbit-to-orbit propulsion. Electric propulsion, which has a high I_{sp} but low thrust, can be applied to orbit-to-orbit transfers of cargo. Trip time from LEO to lunar orbit, for example, is about 100 days, as opposed to 3 days for rocket propulsion. And loss of effective thrust (gravity loss) is experienced in the vicinity of the planets (causing most of the trip time to be spent near the planets). But specific impulses of 1000 to 3000 seconds for advanced electric thrusters still give the systems high fractions of payload mass to starting mass. Electric propulsion is discussed by Phil Garrison.

Tethers could be used to supply some momentum to orbit-orbit transfers. Near-Earth orbit-orbit transfers might be accomplished without propellant by using conductive, or electrodynamic, tethers. This method is especially good at changing the inclination of orbits and could, for example, change an equatorial orbit to a polar orbit in about a month. This idea is discussed by Andy Cutler.

It is possible that a beamed power system could be used to provide either thermal or electric power for an orbit-orbit transfer. Beamed energy is considered in the paper by Jim Shoji in this propulsion part of the volume and in a paper by Ed Conway in the part on power.

Orbit-orbit transfers outside cislunar space can benefit from alternative technologies, because the trip times are long and, for manned missions, the payloads required for safe return to Earth are large. For these missions, electric propulsion, nuclear propulsion, or, for cargo, light sails (Sauer 1976 and 1977) may become the technology of choice for economically feasible payload-to-starting-mass fractions. Beamed power over these distances is infeasible with antenna sizes suitable for power sources in Earth orbit.

Surface Transportation (On the Moon)

Surface transportation technology on the Moon resembles that on Earth (see fig. 6). The major difference is that radiation protection must be provided for personnel. Among other things, this implies that base modules will be connected by trenches and tunnels. The machinery to produce these must be part of the base construction equipment. It also implies intensive use of vehicle teleoperation for activities on the lunar surface (see fig. 7). Teleoperation was not treated in detail by our group but has been considered by Rob Lewis in workshop 4.

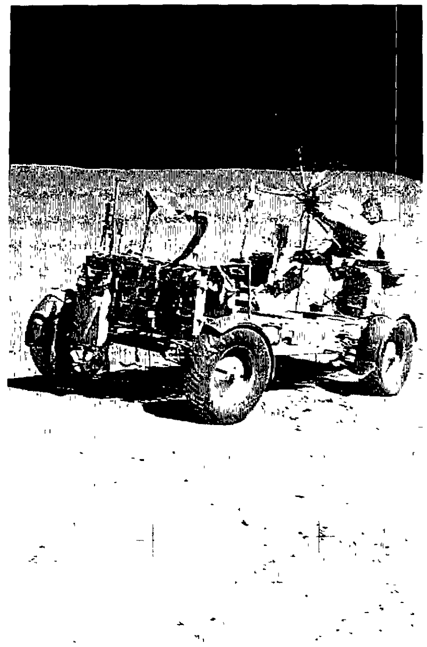


Figure 6

Rover Used on the Apollo 16 Mission

The astronaut is aiming the antenna toward Earth at one of the stops. This rover offers no radiation protection other than the space suits of the astronauts

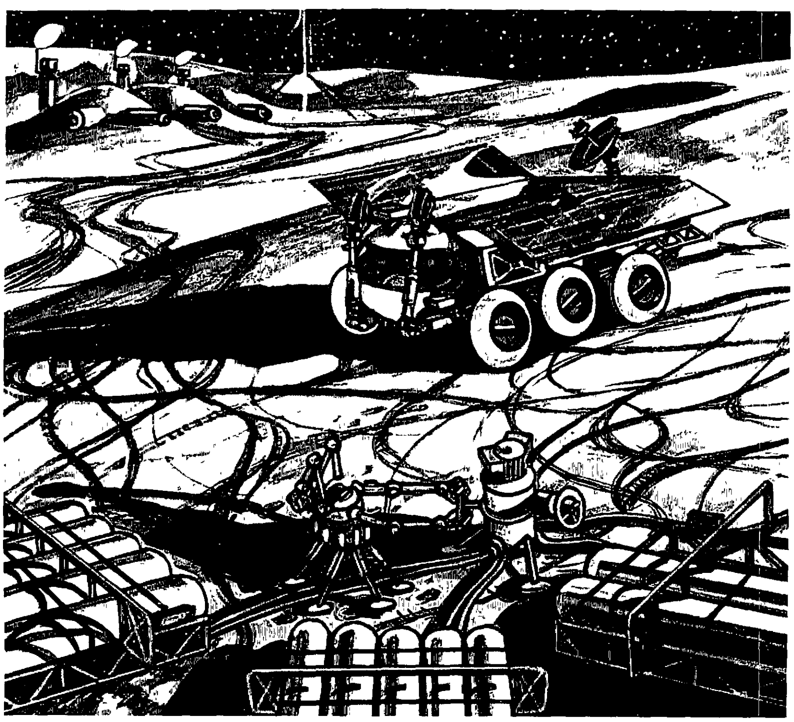


Figure 7

Teleoperated Rover at a Lunar Base

The rover in this artist's conception is powered by batteries which are recharged by the solar cell panels. While designed mainly for teleoperation, the vehicle has a cab so that it can be used for manned operation or human transport.

A second difference is that lunar surface vehicles must function in a vacuum. Besides the obvious requirement for passenger life support, there is the requirement that external mechanisms be successfully lubricated, in a dusty vacuum, without significant outgassing. The technical difficulties involved have yet to be seriously addressed.

It should be noted that logistics support will be required at each node. This logistics support is itself an important transportation technology; it absorbs the lion's share of transportation funding.

The logistics support at all nodes will contain some kind of repair and maintenance facilities and will make provision for refueling, including storage and handling of cryogens. Neither has yet been done routinely by NASA in space. In the short run, there will have to be major facilities only on the Earth's surface and in LEO. In the long run, facilities will probably be placed on the Moon and at other nodes as well (see fig. 8). These facilities will contribute a considerable portion of the system's operating cost. To our knowledge, the technology of logistics support has not received the attention it is due.

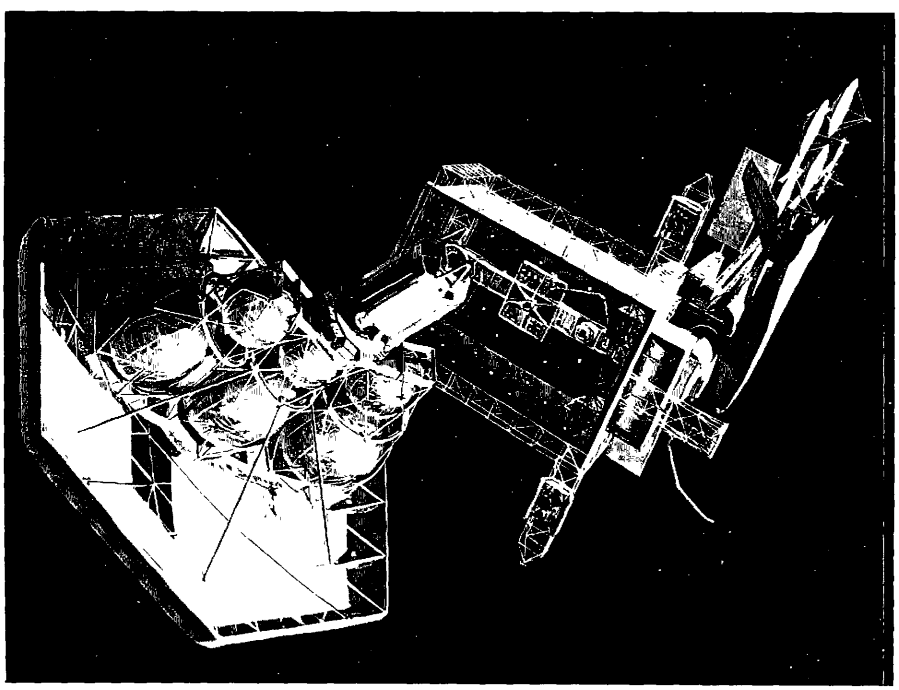


Figure 8

Space Servicing

As the hardware for complex space operations is developed, the technology for maintaining complex hardware in space must also be developed. Here is a General Dynamics concept for a space hangar and maintenance facility associated with the space station. This facility can be used to refuel, service, and repair the orbital transfer vehicle shown in the foreground.

Effects of Developing Nonterrestrial Resources

The development of nonterrestrial resources will have mixed effects on the space transportation system. On the one hand, the establishment of nonterrestrial manufacturing facilities will increase the load on the transportation system early in the program. On the other hand, once these facilities are established, they will reduce transportation requirements by providing propellant at various transportation nodes. This propellant can then be used to support cis- and translunar missions.

Intensive development of GEO could also make good use of nonterrestrial resources, in much the same way as would a Mars expedition. In addition, structural members of a GEO platform could be fabricated on the Moon.

Intensive use of cislunar space for the Strategic Defense Initiative (SDI) would almost demand use of lunar or asteroidal materials for shielding. And the transportation requirements of the SDI would probably be large enough to merit use of nonterrestrial propellants.

Remarks

Because of our assumptions, we have overlooked some technologies. We have not considered nuclear propulsion in cislunar space, for example, as it does not seem advantageous over such short distances. We have not considered several very speculative forms of transportation, such as fusion power and antimatter, because they seem technically uncertain or simply inapplicable. A good overview of advanced propulsion systems may be obtained from work by Robert L. Forward (1983) and a Jet Propulsion Laboratory report edited by Robert H. Frisbee (1983).

Some privately funded groups are apparently interested in funding specific experimental work in certain advanced propulsion technologies. NASA should consider cooperation with such groups as a way to extend seed money.

In summary, it seems likely that OH rocket engines will be indispensable for the foreseeable future. It is at least possible that such rockets are best used in conjunction with other technologies. It is therefore advisable to spend enough seed money to ensure that these other technologies are available when needed.

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Utilization of Space Resources in the Space Transportation System

Michael C. Simon

Utilization of space resources (i.e., raw materials obtained from nonterrestrial sources) has often been cited as a prerequisite for large-scale industrialization and habitation of space. While transportation of extremely large quantities of material from Earth would be costly and potentially destructive to our environment, vast quantities of usable resources might be derived from the Moon, the asteroids, and other celestial objects in a cost-effective and environmentally benign manner.

Of more immediate interest to space program planners is the economic feasibility of using space resources to support near-term space activities, such as scientific and commercial missions in the 2000-2010 timeframe. Liquid oxygen for use as a propellant in a space-based transportation system appears to be the space resource that has the firmest near-term requirement for quantities great enough to be produced economically in a nonterrestrial setting. This paper identifies the factors most likely to influence the economics of near-term space resource utilization. The analysis is based on a scenario for producing liquid oxygen from lunar ore.

Analysis Methodology

The primary purpose of the parametric cost model developed as part of this study is to identify the factors that have the greatest influence on the economics of space resource utilization. In the near term, this information can be used to devise strategies for technology development so that capabilities developed will produce cost-effective results.

Predicting the actual costs of particular scenarios for space resource utilization is only a secondary objective of this analysis. Estimates are made and dollar values are assigned principally to allow comparison of options. Since the technologies for space resource utilization are in an early stage of development, it is premature to state conclusively whether mining the Moon, asteroids, or other celestial bodies makes economic sense. The parametric model is designed more for flexibility than for precision.

Although preliminary estimates indicate that production of oxygen from lunar ore is a project that is likely to yield an economic payback, this activity was selected as the "baseline scenario" primarily because its requirements can be relatively well defined. The major systems required to support this baseline scenario have been identified without much difficulty:

- A processing and storage facility to manufacture liquid oxygen (LO_2) from lunar ore and store it on the Moon
- A lunar habitat for a small, full-time crew
- A power system to support lunar LO_2 operations
- A transportation and logistics system to deliver and support the lunar base elements and to transport the LO_2 to low Earth orbit (LEO)

Systems Required To Support Production of Oxygen From Lunar Ore

This concept of a lunar base shows an oxygen plant in the foreground, habitats buried on the left, solar power systems for heat (at the plant) and light (for the habitats), ground transportation (trucks bringing ore and taking away products), and a surface-to-orbit ferry in the background. The same systems are pictured in the frontispiece, in the background on the right: reactors with their solar power, habitats being buried, a vehicle picking up products and transporting them to the launch area, a tanker just lifting off.

Once these major support systems were defined, fifteen key variables were identified as influencing the cost of developing and operating these systems (table 3). Cost variables were generalized so that the parametric model could be adapted to the evaluation of alternative scenarios. Next, equations were developed to calculate capital and operations costs as functions of these variables. Using the codes and units detailed in table 3, these equations are

$$\text{Capital cost} = (p \times c_p) + (n_t \times c_n) + (n_m \times c_u) + c_f + c_t \times [(p \times m_p) + (n_m \times m_m) + m_f]$$

$$\text{Operations cost} = c_t \times \{(n_r \times m_m) + [(1\text{-}d) \times 125\ 000]\} + (n_b \times n_f \times \$100\ 000)$$

where the capital cost is defined as the total cost of developing, building, and installing the lunar base elements (including transportation costs) and the operations cost is the annual cost of manufacturing 1 million kilograms (1000 metric tons) of LO_2 per year and delivering to LEO as much of this LO_2 as possible.

The term in square brackets [(1-d) x 125 000] in the operations cost equation reflects the assumptions that a portion (1-d) of the LO_2 produced on the Moon is used as propellant to deliver the remaining LO_2 (d) to LEO and that 1 kilogram of hydrogen must be delivered from Earth to the Moon for every 8 kilograms of oxygen used as propellant for the Moon-to-LEO leg (125 000 kg of hydrogen for the projected annual production of 1 million kg of oxygen). The higher-than-usual mixture ratio of 8:1 was selected for the baseline case after initial analyses showed that the resultant reduction in the hydrogen requirement offers substantial economic benefits.

The constant cost ($100 000) in the operations cost equation is the cost of ground support per provider per year. The variable that precedes this constant, n_f, is a ground support overhead factor which is multiplied by the labor cost to obtain total ground support cost.

TABLE 3. *Lunar Oxygen Production—Major Cost Variables*

Variable	Code	Units of evaluation
Power required	p	Megawatts of installed capacity
Cost of power	c_p	Nonrecurring cost ($) per megawatt of installed capacity
Number of types of lunar base modules	n_t	Number of types
Cost of modifying space station modules	c_n	Nonrecurring cost ($) for adapting each type of module
Number of lunar base modules	n_m	Number of units
Unit cost of lunar base modules	c_u	Recurring cost ($) of producing each lunar base module
Processing/storage facility cost	cf	Development and production cost ($)
Earth-to-Moon transportation cost	c_t	Cost ($) per kilogram delivered from Earth to the Moon
Power system mass	m_p	Kilograms per megawatt of installed capacity
Unit mass of lunar base modules	m_m	Mass (kilograms) of each lunar base module
Mass of processing/storage facility	m_f	Kilograms
Number of lunar base resupply missions/year	n_r	Number
Net lunar oxygen delivered to LEO	d	Fraction of lunar LO_2 produced which is delivered to LEO
Ground support labor	n_b	Number of people (full-time)
Ground support overhead factor	n_f	Multiplier of labor cost needed for total cost

After these cost equations had been set up, baseline values were assigned to each cost variable, using the ground rule that the technology having the lowest risk would be used for each system. Lunar base modules, for example, were assumed to be modified versions of the laboratory, habitat, and logistics modules that are being developed for NASA's LEO space station.

Another ground rule was that the costs of gathering the scientific data needed to select the lunar processing site would not be included in this model. It was further assumed that an initial lunar base would be in place prior to the LO_2 production activity and that this facility would be scaled up to meet the LO_2 production requirements. Thus, the cost included in this model is only the marginal cost of expanding this initial facility to produce LO_2.

Although some of these ground rules lowered capital and operations cost estimates, the specification of lowest-risk technology made these estimates higher than they might be if cost-reducing technologies are developed.

Results of the Analysis

Once baseline values were assigned to the cost variables, a simple calculation was made to obtain capital and operations cost estimates. These costs were determined to be

Capital cost: $3.1 billion
Operations cost: $885 million/year

An analysis of the performance of proposed lunar orbital transfer vehicles (OTVs) indicates that 49.2 percent of the LO_2 produced would be delivered to LEO. Consequently, the unit cost of LO_2 delivered to LEO, assuming 10-year amortization of capital costs, was determined to be $2430/kg ($1100/lb). This cost is one-quarter to one-third of the current cost of using the Space Shuttle, although it is somewhat greater than the cost that might be achieved with a more economical next-generation Earth-launched vehicle.

It should be reemphasized, however, that all cost estimates used in this analysis are based on a specific set of assumptions and are for comparative purposes only. The most important objectives of this analysis were the assignment of uncertainty ranges to each of the cost variables, the calculation of the sensitivity of LO_2 production costs to each of these variables, and the analysis of the technical and programmatic assumptions used to arrive at values for each variable. The data developed to support the sensitivity analysis are summarized in table 4. The baseline, best case, and worst case values assigned to each cost variable are shown, along with the impact of each variable's best case and worst case values on capital or operations cost. For example, as power requirements vary from a low value of 4 MW to a high value of 12 MW, with all other variables held at their baseline values, the capital cost for establishing the LO_2 production capability ranges from $2.30 billion to $3.90 billion.

From this table it is evident that the principal driver of capital cost is the lunar base power requirement, while the Earth-to-Moon transportation cost is the most important operations cost driver. Since capital costs are amortized over a 10-year period, the Earth-to-Moon transportation cost has a much greater overall impact on the cost of lunar LO_2 in LEO. If this cost could be reduced from its

TABLE 4. *Capital and Operations Costs—Sensitivity to Cost Variables*

Variable	Baseline case	Best case		Worst case	
	Most likely value	Value	Result	Value	Result
	Capital cost				
1. Power required	8 MW	4 MW	$2.30B	12 MW	$3.90B
2. Cost of power	$100M/MW	$50M/MW	$2.70B	$200M/MW	$3.90B
3. Number of types of lunar base modules	1	0	$2.80B	2	$3.40B
4. Cost of modifying space station modules	$300M	$100M	$2.90B	$500M	$3.30B
5. Number of lunar base modules	1	1	$3.10B	3	$3.90B
6. Unit cost of lunar base modules	$200M	$100M	$3.00B	$300M	$3.20B
7. Processing/storage facility cost	$500M	$300M	$2.90B	$1.0B	$3.60B
8. Earth-to-Moon transportation cost	$10 000/kg	$5000/kg	$2.45B	$15 000/kg	$3.75B
9. Power system mass	10 000 kg/MW	5000 kg/MW	$2.70B	15 000 kg/MW	$3.50B
10. Unit mass of lunar base modules	20 000 kg	15 000 kg	$3.05B	30 000 kg	$3.20B
11. Mass of processing/storage facility	30 000 kg	15 000 kg	$2.95B	50 000 kg	$3.30B
	Operations cost				
1. Number of lunar base resupply missions/yr	1	1	$885M/yr	3	$1.285B/yr
2. Net lunar oxygen delivered to LEO	49.2%	70%	$625M/yr	30%	$1.125B/yr
3. Ground support labor	20 people	10 people	$860M/yr	50 people	$960M/yr
4. Ground support overhead factor	25	5	$845M/yr	50	$935M/yr
5. Earth-to-Moon transportation cost	$10 000/kg	$5000/kg	$468M/yr	15 000/kg	$1.303B/yr
6. Unit mass of lunar base modules	20 000 kg	15 000/kg	$835M/yr	30 000 kg	$985M/yr

baseline value of $10 000 to its best case value of $5000 per kilogram delivered to the Moon, capital cost would drop from $3.1 billion to $2.45 billion, operations cost would decline from $885 million/year to $468 million/year, and the cost of lunar LO_2 would be reduced from $2430/kg to $1450/kg. Conversely, at its worst case value of $15 000/kg, the Earth-to-Moon transportation cost would drive capital cost up to $3.75 billion, operations cost to $1.303 billion/year, and the cost of lunar LO_2 to $3410/kg.

An alternative approach to showing the impacts of the cost variables is illustrated in table 5. It lists the effect of each cost variable in terms of percentage changes in the capital or operations cost and in the cost per kilogram of LO_2 produced (with a 10-year amortization of capital cost). In this table the variables are ranked in order of their impact on the LO_2 cost/kg. The influence of each variable is calculated as an "impact factor" equal to the average of the percentage changes in LO_2 cost/kg due to the best-case and worst-case values of the variable.

TABLE 5. *Sensitivity of Capital, Operations, and Oxygen Production Costs to Ranges of Cost Variables*

Variable	Sensitivity ranking	Best case: Change in total cost	Best case: Change in LO_2 cost/kg	Worst case: Change in total cost	Worst case: Change in LO_2 cost/kg	Impact factor
Capital cost						
Earth-to-Moon transportation cost	1	-21%	-40%*	+21%	+40%	40
Power required	2	-26%	- 7%	+26%	+ 7%	7
Unit mass of lunar base modules	3	- 2%	- 4%*	+ 3%	+ 9%	7
Cost of power	4	-13%	- 3%	+26%	+ 7%	5
Number of lunar base modules	5	0%	0%	+26%	+ 7%	4
Processing/storage facility cost	6	- 6%	- 2%	+16%	+ 4%	3
Power system mass	7	-13%	- 3%	+13%	+ 3%	3
Number of types of lunar base modules	8	-10%	- 3%	+10%	+ 3%	3
Cost of modifying space station modules	9	- 6%	- 2%	+ 6%	+ 2%	2
Mass of processing/storage facility	10	- 5%	- 1%	+ 6%	+ 2%	2
Unit cost of lunar base modules	11	- 3%	- 1%	+ 3%	+ 1%	1
Operations cost						
Net lunar oxygen delivered to LEO	1	-29%	-45%	+27%	+97%	71
Earth-to-Moon transportation cost	2	-47%	-40%*	+47%	+40%	40
Number of lunar base resupply missions/yr	3	0%	0%	+45%	+13%	7
Unit mass of lunar base modules	4	- 6%	- 4%*	+11%	+ 9%	7
Ground support labor	5	- 3%	- 3%	+ 8%	+ 6%	5
Ground support overhead factor	6	- 5%	- 3%	+ 6%	+ 4%	4

*Impact based on changes in both capital cost and operations cost

From these impact factors it is clear that two of the cost variables are far more important than all the rest: net lunar oxygen delivered to LEO and Earth-to-Moon transportation cost. The percentage of lunar-produced oxygen delivered to LEO is important because of its double impact. As the percentage of LO_2 delivered declines, LO_2 cost/kg increases not only because less LO_2 is delivered but also because more hydrogen must be transported from the Earth to match the LO_2 used as propellant from the Moon to LEO.

The six operations cost variables are among the nine most important, largely because the impact of capital cost is spread out over the 10-year amortization period. The relative significance of the operations cost leads to the important observation that LO_2 production costs may be reduced substantially by increasing capital expenditure on technologies that can reduce operations cost. One such technology is Earth-to-Moon transportation, which has a tremendous impact on operations cost. Capital cost factors, such as the mass and cost of the power system and of the processing/ storage facility, have much less impact on LO_2 cost/kg.

Technology Development Required To Improve Performance

It is not possible to conclude, on the basis of this analysis, that production of liquid oxygen from lunar materials is justifiable on economic grounds. Although the cost estimates for the baseline scenario are encouraging, a number of technologies with significant impact on LO_2 production costs must be explored. The performance and cost of space-based orbital transfer vehicles is the most critical technology issue. Developing a low-cost OTV is a fundamental requirement for cost-effective utilization of space resources because the OTV is the single most effective means of reducing Earth-to-Moon transportation cost.

Another key issue is the cost of hydrogen used for launching payloads from the Moon. Production of lunar LO_2 would be far more cost-effective if a capability for the co-production of lunar hydrogen could be developed (even though capital cost might increase substantially). Although relatively large quantities of lunar ore would need to be processed, the additional cost of lunar hydrogen production could be offset by a savings of over $600 million/year in transportation cost. Production of some alternative propellant constituent, such as aluminum, also might offer an opportunity for reducing or eliminating costly import of fuels from Earth. However, this example would require the development of an aluminum-burning space engine.

A third category that seems to have substantial impact on the economics of lunar resource utilization is the technologies influencing lunar base resupply requirements. Increasing lunar base automation, closing the lunar base life support system, and other steps to reduce the frequency and scale of resupply missions appear to have a high likelihood of providing economic benefits and should be given particular emphasis in future studies.

If all three of these objectives were met to the greatest extent possible (i.e., if Earth-to-Moon transportation cost were reduced to its best case value, if hydrogen transportation requirements were eliminated, and if lunar base resupply requirements were eliminated), the cost of lunar LO_2 delivered to LEO would be reduced from $2430/kg to $600/kg, or about $270/lb. These figures assume no change in capital cost; but, even if capital cost were doubled to achieve these capabilities, LO_2 cost would be reduced to approximately $1100/kg—less than half the baseline cost.

Twenty-five key technology issues influencing these and the other cost variables in LO_2 production are presented in table 6. In this table, a dark square indicates a stong impact of that technology issue on the cost variable, a light square indicates a moderate impact, and no square indicates little or no impact. The selection and evaluation of these technology issues was made by a panel of experts convened for the purpose, not by a quantitative analysis. The fifteen cost variables ranked as in table 5 are listed across the top of table 6 in descending order of importance. Hence, table 6 is a graphic representation of the relative importance of the technologies based on three considerations: total number of squares, number of dark squares, and distribution of squares to the left of the chart (i.e., toward the most important cost variables).

TABLE 6. *Impact of 25 Key Technology Issues on Cost Variables in Space Resource Utilization*

■ heavy impact

□ moderate impact

(blank) little or no impact

		d Net lunar oxygen delivered to LEO	c_t Earth-to-Moon transportation cost	p Power required	n_r Number of lunar base resupply missions/yr	m_m Unit mass of lunar base modules	c_p Cost of power	n_b Ground support labor	n_m Number of lunar base modules	n_l Ground support overhead factor	c_f Processing/storage facility cost	m_p Power system mass	n_t Number of types of lunar base modules	c_n Cost of modifying space station modules	m_f Mass of processing/storage facility	c_u Unit cost of lunar base modules
		71	40	7	7	7	5	5	4	4	3	3	3	2	2	1
Power	Lunar base power source (nuclear vs. solar)						■					■				
Power	Scalability of small (<100 kW) power systems						■									
Power	Electrical vs. thermal energy						■				□	■			□	
Power	Power consumption of processing technique(s)			■												
Power	Complexity of power system installation						■									
Power	Maintainability of power system				□		■					■				
Operations	Pressurized volume required for lunar operations				□	■			■					□		□
Operations	Duration of lunar base crew shifts				■				□				■	□		□
Operations	Degree of automation of lunar base operations			□	■	□	■	■	■	■	■	□	□	■	■	■
Operations	Size of lunar base crew			□	■	■		■	■				■			
Operations	Self-sufficiency of lunar operations			□	■	■		■	■	□	□		■		□	
Operations	Ground support approach							■		■						
Base	Commonality of lunar base module w/ space station modules													■		■
Base	Lunar base shielding requirements					■								□		□
Base	Space station interfaces													□		
Base	Scalability of initial lunar research facilities			□			□		□			□	□			
Base	Degree of closure of lunar base life support system				■	■		■	□	□			□	□		□
Factory	Complexity of lunar factory processes			□	□	□		□	□		■		□	□	■	□
Factory	Number of lunar factory processes			□	□	□		□	□		■		□		■	
Factory	Commonality of processing facility w/ space station lab modules										■				□	
Factory	Commonality of LO_2 storage unit w/ OTV propellant depot										■					
Factory	Availability of lunar hydrogen	■		■				□			■				■	
Transport	Performance and cost of SDLV/HLLV (if available)		■													
Transport	Performance and cost of OTV (if available)	■	■		□			□								
Transport	Availability of aerobrake for LO_2 delivery	■														

To quantify the impact of these twenty-five technology issues on the economics of the baseline scenario for space resource utilization, a technology weighting factor of 3 was assigned to each dark square and a factor of 1 to each light square. These technology weighting factors were then multiplied by the impact factor (table 5) for each cost variable that the technology issue affects. The sum of the products across each row was calculated as the total economic weighting factor for that technology issue. For example, the lunar base power source has a heavy impact on cost of power and power system mass for an economic weighting factor of (3 x 5) + (3 x 3) = 24.

The ten most important technology issues, according to their total economic weighting factors, are listed in table 7.

TABLE 7. *Major Technology Issues in the Cost-Effective Production of Lunar Oxygen*

Issue	Economic weighting factor*
1. Performance and cost of OTVs	345
2. Availability of lunar hydrogen	254
3. Availability of aerobrake for LO_2 delivery	213
4. Performance and cost of Shuttle-derived launch vehicle (SDLV) or heavy lift launch vehicle (HLLV)	120
5. Degree of automation of lunar base operation	119
6. Self-sufficiency of lunar operation	94
7. Size of lunar base crew	85
8. Degree of closure of lunar base life support system	71
9. Complexity of lunar factory processes	51
10. Number of lunar factory processes	48

*Each of 25 key technology issues was assessed with respect to its influence on the 15 cost variables Weights were assigned on the basis of the subjective judgment of a panel of experts These weights were multiplied by an "impact factor" for each cost variable (based on the sensitivity of the cost of lunar LO_2 to the variable) affected by the technology issue

Finally, it is important that parametric cost analyses such as this one be used to assess a variety of space resource utilization scenarios. Use of lunar ore for production of construction materials is one such option, although to be cost-effective this type of enterprise would probably require a dramatic increase in space activity. Another option that merits careful consideration is the development of asteroidal resources. Both rocket propellants and construction materials could be derived from asteroids; and, while the up-front cost of asteroid utilization would probably exceed the capital expenditure required for lunar development, operations cost could be substantially lower. Further analysis of all these opportunities needs to be carried out over the next several years before a commitment is made to any particular plan for space resource utilization.

As new technologies are developed, the reliability of cost estimates for space resource utilization will improve. Eventually, it will be possible to generate cost estimates of sufficient fidelity to support detailed definition of space utilization objectives. An important step in this process will be the adaptation of this parametric model and similar techniques to the evaluation of a broad range of space resource development options.

Aluminum-Fueled Rockets for the Space Transportation System

Andrew H. Cutler

Introduction

Aluminum-fueled engines, used to propel orbital transfer vehicles (OTVs), offer benefits to the Space Transportation System (STS) if scrap aluminum can be scavenged at a reasonable cost. Aluminum scavenged from Space Shuttle external tanks (fig. 9) could replace propellants hauled from Earth, thus allowing more payloads to be sent to their final destinations at the same Shuttle launch rate.

To allow OTV use of aluminum fuel, two new items would be required: a facility to reprocess aluminum from external tanks and an engine for the OTV which could burn aluminum. Design of the orbital transfer vehicle would have to differ substantially from current concepts for it to carry and use the aluminum fuel. The aluminum reprocessing facility would probably have a mass of under 15 metric tons and would probably cost less than $200 000 000. Development of an aluminum-burning engine would no doubt be extremely expensive (1 to 2 billion dollars), but this amount would be adequately repaid by increased STS throughput. Engine production cost is difficult to estimate, but even an extremely high cost (e.g., $250 000 000 per engine) would not significantly increase orbit-raising expenses.

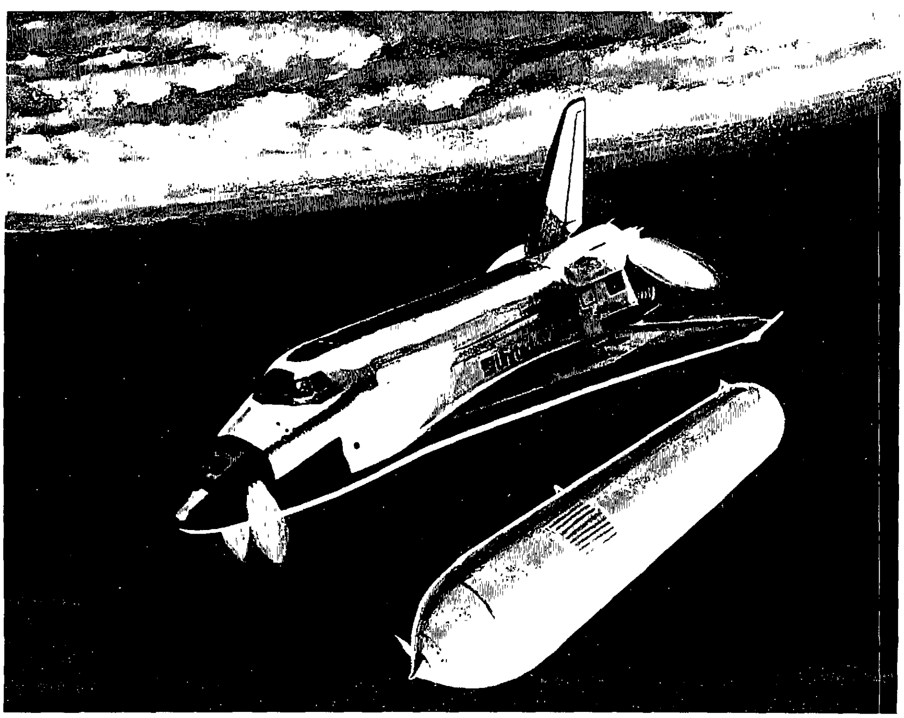

Figure 9

Separation of the External Tank From the Shuttle Orbiter

The external tank, which carried the liquid hydrogen and liquid oxygen for the main engines of the orbiter, is 28 feet (8 5 meters) in diameter and 157 feet (47 9 meters) long In current operations. before the Shuttle reaches orbit, the tank is released from the orbiter. follows a ballistic trajectory, and falls into a remote area of the ocean With a slight adjustment of the orbiter's trajectory and the release point. these tanks could be carried into low Earth orbit

A new NASA policy has been implemented which encourages use of these jettisoned external tanks. They will be made available in low Earth orbit for both commercial and nonprofit endeavors and NASA will accept proposals to use them. Between 1989 and 1994, approximately 40 external tanks will be flown. The number that would be available to private ventures will depend on a case-by-case analysis of each Space Shuttle launch and the proposed use for that particular tank.

The combustion of aluminum delivers 22 percent more energy per unit mass of reactant than does the combustion of hydrogen. Since propellant costs on the Earth are a small part of total launch costs, the added complexity of tripropellant engines is not warranted for launch from the Earth's surface. However, if aluminum fuel were available in low Earth orbit (LEO) at a much lower cost than cryogenic fuel, the savings in propellant cost could offset the cost of developing an aluminum-fueled space engine.

Background

Aluminum-fueled rockets are ubiquitous. Aluminum is added to the solid fuel of rockets to enhance their performance. Most ground-based solid rockets are aluminized. Solid rockets intended for launch in space are following this trend (e.g., the inertial upper stage—IUS—rockets). The Space Shuttle itself burns twice as much aluminum (in the solid rocket boosters—SRBs) as it does hydrogen (total of the elemental hydrogen in the external tank and the chemically combined hydrogen in the SRB fuel).

The aluminum oxide (Al_2O_3) produced by the Shuttle's combustion of aluminum quickly settles out of the atmosphere. That produced by rockets taking satellites to geosynchronous Earth orbit (GEO) does remain there. The Al_2O_3 would be a pollutant in cislunar space. However, the dilution is such that aluminum oxide pollution there should not be a severe problem for a long time.

Experiments have shown that aluminum additives can also enhance the performance of liquid-fueled rockets. The combined efforts of those working on solid and liquid propellant rockets might have an increased total effect if they were focused on the development of an aluminum-fueled space engine.

Aluminum Availability in LEO

Aluminum could be made readily available as a fuel in LEO. The 1988 National Space Policy offers Shuttle external tanks (ETs) free to users in space. (The conditions include demonstrating that any reentry of the tanks can be controlled.) External tanks could be carried to orbit for little additional cost and with little adverse impact on Shuttle operations. These tanks could then be reprocessed to provide fuel aluminum.

Aluminum would probably be burned in the form of micron-sized powder. From extrapolations of current mission models, the maximum projected aluminum demand is about 14 metric tons per tank. This amount of aluminum could be recovered in the following manner (see fig. 10): All gas is vented from the tanks. A cutting machine with an electron beam cutter (demonstrated on Skylab for 2219 aluminum alloy) enters the tank. It makes circumferential cuts in the barrel sections and in the ogive (pointed arch section) immediately adjacent to the ring frames. The cuts do not cross the cable tray. These circumferential cuts are connected by longitudinal cuts along both sides of the cable tray and between the ring frames.

Since the cutting is done while the thermal protection system (TPS) is still intact, all spatter and fumes will be contained inside the tank and may be trapped to prevent extensive contamination of the local area. "C"-shaped sections of the tank composed of a metal sheet coated on one side with TPS material may now be broken loose. These "C"s contain the needed 14 metric tons of 2219 aluminum alloy, so the remainder of the tank—ring frames, intertank (section between the hydrogen and oxygen tanks), slosh baffles, end domes, and cable tray—may be discarded.

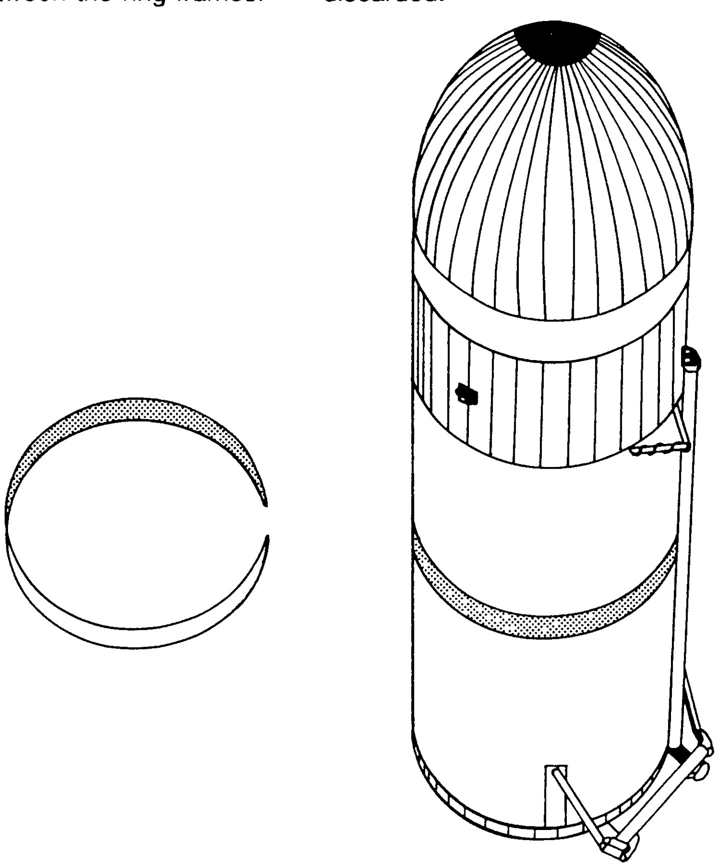

Figure 10

Reprocessing of Space Shuttle External Tank

"C"-shaped sections could be cut from the most accessible parts of the external tank, leaving the cable tray and other complex parts to be discarded. The aluminum strips could then be rolled onto a mandrel, melted, and sprayed against a rapidly rotating wheel to produce the aluminum powder needed as fuel for a new type of engine for an orbital transfer vehicle.

The aluminum strips may then be rolled onto a mandrel to densify them for melting. The bulk of the TPS coating will separate from the aluminum sheet while it is being rolled up. The small amount of TPS material remaining on the sheet can be removed with a rotating wire brush and discarded along with the other unprocessed materials. The rolled aluminum strip is placed in an induction furnace and melted. The liquid aluminum can be pumped from this pool and turned into powder the same way it is on Earth—by being sprayed against a rapidly rotating wheel. The vacuum of space allows efficient electron beam cutting and prevents oxidation of the aluminum powder as it is being formed.

The operation described here requires further study. Among the problems to be solved is that of disposing of the residual portions of the external tank in an environmentally acceptable way. The generation of large or small debris (e.g., pieces of insulating material) that cannot be controlled could make the aluminum scavenging concept untenable.

The amount of aluminum available in the external tanks is far larger than the amount of aluminum fuel needed. Only the most easily reprocessed part of the tanks need be worked on. These portions of the tank are composed of only one alloy, 2219, which has been extensively characterized in commercial use. These facts combined with the fact that the plant makes only one product (aluminum powder) suggest that the plant will be simple, reliable, and economical.

Aluminum as a Propellant

The combustion of aluminum by oxygen is very energetic. Most of the energy is released as aluminum oxide condenses from the gas phase. Aluminum oxide condensation in the rocket nozzle is a rapid process. Condensation of aluminum oxide heats the gas, which expands to provide thrust. Since the aluminum oxide particles do not completely exchange momentum and energy with the gas phase, there is some impulse reduction due to two-phase flow loss. The two-phase flow loss must be controlled by including in the exhaust a gas with low molecular weight (Frisbee 1982). Hydrogen is the ideal candidate. An oxygen-hydrogen-aluminum engine with a mixture ratio of 3:1:4 is expected to have a specific impulse of over 400 seconds, and eventually it might achieve a specific impulse of over 450 seconds (Cutler 1984).

Propellant Demand in LEO

Much of the mass currently lifted to LEO is propellant for orbit raising and maneuvering. According to OTV transportation models (table 8), 45-180 metric tons of payload mass per year will be lifted to geosynchronous Earth orbit as soon as an OTV is available or expendable rockets can be fueled at the space station. To lift these payloads from LEO to GEO, 90-360 metric tons of propellants will be required in LEO. The specific propellant requirement depends on the design and performance of the OTV used, including whether or not it is reusable. In this paper, I have assumed a propellant-to-payload ratio of 2:1. Some of this (130-325 metric tons per year) can be scavenged from the Space Shuttle's external tank in the form of unused hydrogen and oxygen (see table 9).

TABLE 8. *Models for Orbital Transfer Vehicle Traffic*

Model	Payload size, metric tons	Mass to GEO per year, metric tons
Cooper[a]	6.82	122 9
Current comsats	1 14	45.5
Advanced comsats	4.55	182
General Dynamics[b]	4.55	54 6
Eagle Engineering[c]	15.3	Not specified

[a]Lawrence P Cooper, 1984, Propulsion Issues for Advanced Orbital Transfer Vehicles, NASA TM-83624
[b]Michael C Simon, personal communication
[c]Hubert P Davis, 1983, Lunar Base Space Transportation System, Eagle Engineering report EEI 83-78

Aluminum-Fueled Engines for OTV Propulsion

Table 9 shows the amounts of O-H and O-H-Al propellant usable under different conditions. If the traffic model requires more propellant than can be scavenged, additional propellant must be carried in place of payloads of greater intrinsic value or new technology must be introduced to improve performance.

Marginal improvements can be made in OTV performance by incorporating advanced cryogenic engines. Improving engine performance from the current I_{sp} of 460 seconds to an I_{sp} of 480-490 seconds would allow 7-11 percent more payload to be carried to GEO with the same cryogenic propellant supply.

If oxygen-hydrogen-aluminum engines were available (and relatively small amounts of hydrogen

TABLE 9. *Usable Propellant Available in LEO Yearly*
[In metric tons]

Model parameters	Cryogens for use in 6:1 O-H engine	Aluminum for use in 3:1:4 O-H-Al engine	With additional hydrogen[a]	Total propellants usable in 3:1:4 O-H-Al engine
24 flt./yr, loaded at 75% of maximum mass	325	372	46	743
24 flt./yr, loaded at 100% of maximum mass	129	148	18	295
Martin Marietta study,[b] standard ET	196	224	28	448
Martin Marietta study,[b] ET with aft cargo carrier	130	148	19	297

[a]Because the ratio of hydrogen to oxygen is twice as high in the O-H-Al engine as it is in the O-H engines (OTV and Shuttle), additional hydrogen from Earth would be needed in order to use all the scavengeable oxygen

[b]Martin Marietta, Michoud Division, 1984, STS Propellant Scavenging Systems Study, Addendum to Performance Review, performed under contract NAS8-35614, Jan The Martin Marietta mission model has been normalized to 24 flights to the space station per year, a slightly higher rate than that used in the study

could be added), the amount of scavengeable propellants would double (table 9). Besides the aluminum to match the scavenged hydrogen and oxygen, there would be excess aluminum to match hydrogen and oxygen transported from Earth, thus doubling its effectiveness.

A simplified cost model is shown in figure 11.

If the assumptions used here are shown to be valid, the model indicates that significant cost savings can be made, even at low traffic levels, by scavenging cryogens from the Space Shuttle and, at higher traffic levels (above 90 metric tons per year), significant cost savings could also be made by scavenging aluminum from the external tank.

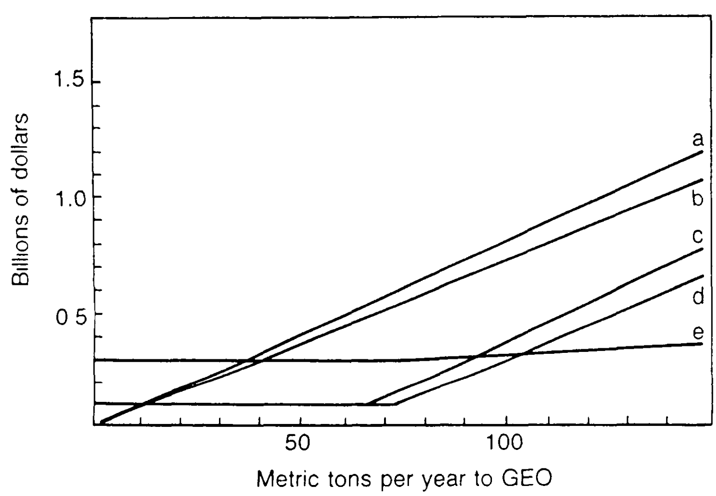

Figure 11

Relative Propellant Costs for Orbital Transfer

This figure shows the relative propellant costs for lifting payloads from low Earth orbit (LEO) to geosynchronous Earth orbit (GEO) using (a) *all propellant from Earth at $4000/kg,* (b) *all propellant from Earth and an advanced cryogenic engine,* (c) *scavenged cryogenic propellants,* (d) *scavenged cryogenic propellants and the advanced cryogenic engine, and* (e) *scavenged aluminum as well as scavenged oxygen and hydrogen*

The weight of the orbital transfer vehicle (OTV) is ignored, and the propellant-to-payload ratio is assumed to be 2 1 Cryogen scavenging is assumed to cost $100 000 000 per year and aluminum scavenging is assumed to cost an additional $200 000 000 per year Cryogens in excess of scavenging availability are taken to cost $4000 per kg delivered to LEO The amounts of scavengeable materials available are those presented in the second model in table 9.

Line a *represents the current practice, in which an oxygen-hydrogen engine boosts a payload using twice its weight in propellant which was brought to LEO at a cost of $4000 per kg. Line* b *represents a similar practice but with an advanced engine that is 10% more efficient. Line* c*, representing the use of the current engine with scavenged cryogens, stays at the cost of scavenging the cryogenic propellants until they are used up [when the payload equals 1/2 the scavengeable amount (129 metric tons in the second model in table 9)], and then goes up with the same slope as that of line* a*. Line* d *represents the use of the advanced engine with scavenged cryogens, and thus it starts going up at about 72 metric tons (the amount of payload that can be carried with the 129 metric tons of scavenged cryogens with an engine that is 10% more efficient) and then parallels line* b*. Line* e *represents the practice the author is advocating--the use of an oxygen-hydrogen-aluminum engine. It stays at the combined cost of scavenging both cryogens and aluminum until all the scavenged hydrogen, about half the scavenged oxygen, and an equal amount of aluminum is used up (at about 74 metric tons of payload). Then this line rises very slowly to cover the cost of bringing to LEO from Earth the additional hydrogen needed to match up with the remaining half of the scavenged oxygen and an equal amount of the abundant scavengeable aluminum. Cryogen scavenging can be a very cost-effective strategy even at low traffic levels. Aluminum scavenging could be effective above 90 metric tons per year of traffic (where line* e *crosses line* c*).*

Conclusion

Aluminum-fueled space engines may be more economical than advanced cryogenic engines in the regimes where advanced engines can offer significant savings over current technology (that is, where there is enough traffic that the benefits from improved performance exceed the cost of developing a new engine). Thus, assuming that all programs for the development of new engines have about the same cost, any argument which justifies developing advanced oxygen-hydrogen engines justifies investigating the development of an aluminum-fueled space engine. The most economical way to run an OTV program may be to rely on an OTV with a current RL-10 engine until propellant demand is near the scavenged supply and then change over to an OTV propelled by an oxygen-hydrogen-aluminum engine.

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Electromagnetic Launch of Lunar Material

William R. Snow and Henry H. Kolm

Introduction

Lunar soil can become a source of relatively inexpensive oxygen propellant for vehicles going from low Earth orbit (LEO) to geosynchronous Earth orbit (GEO) and beyond. This lunar oxygen could replace the oxygen propellant that, in the current plans for these missions, is launched from the Earth's surface and amounts to approximately 75 percent of the total mass. Besides the LEO-to-GEO missions, a manned Mars mission could benefit from this more economical oxygen. The use of such oxygen in a chemical rocket would eliminate the need to develop an advanced nonchemical propulsion technology for this mission. And the shorter trip time afforded by a chemical rocket would also reduce life support requirements.

The reason for considering the use of oxygen produced on the Moon is that the cost for the energy needed to transport things from the lunar surface to LEO is approximately 5 percent the cost from the surface of the Earth to LEO. This small percentage is due to the reduced escape velocity of the Moon compared with that of the Earth. Therefore, lunar derived oxygen would be more economical to use even if its production cost was considerably higher than the cost of producing it on Earth.

Electromagnetic launchers, in particular the superconducting quenchgun, provide a method of getting this lunar oxygen off the lunar surface at minimal cost. This cost savings comes from the fact that the superconducting quenchgun gets its launch energy from locally supplied, solar- or nuclear-generated electrical power. By comparison, unless hydrogen can be found in usable quantities on the Moon, the delivery of oxygen from the Moon to LEO by chemical rocket would cost much more, primarily because of the cost of bringing hydrogen for the rocket from Earth.

Lunar Oxygen Supply Concept

Various methods by which lunar oxygen could be delivered from the surface of the Moon to lunar orbit and on to LEO have been studied by a number of investigators (Clarke 1950; Salkeld 1966; Andrews and Snow 1981; Snow, Kubby, and Dunbar 1982; Davis 1983; Bilby et al. 1987; Snow et al. 1988; LSPI 1988). A diagram of the Earth-Moon system showing the orbits and missions for the lunar oxygen delivery concept that we recommend is shown in figure 12.

The mission scenario starts with the launching of tanks containing 1 metric ton or more of liquid oxygen from an electromagnetic launcher (superconducting quenchgun) on the lunar surface into low lunar orbit (100-km altitude), as shown in figures 13 and 14. When the tank reaches apolune (maximum altitude), a small thruster is fired to circularize its orbit and keep it from crashing back into the lunar surface. With a launch rate of one every 2 hours, the liquid oxygen tanks collect at one spot in lunar orbit. After a number of these tanks accumulate

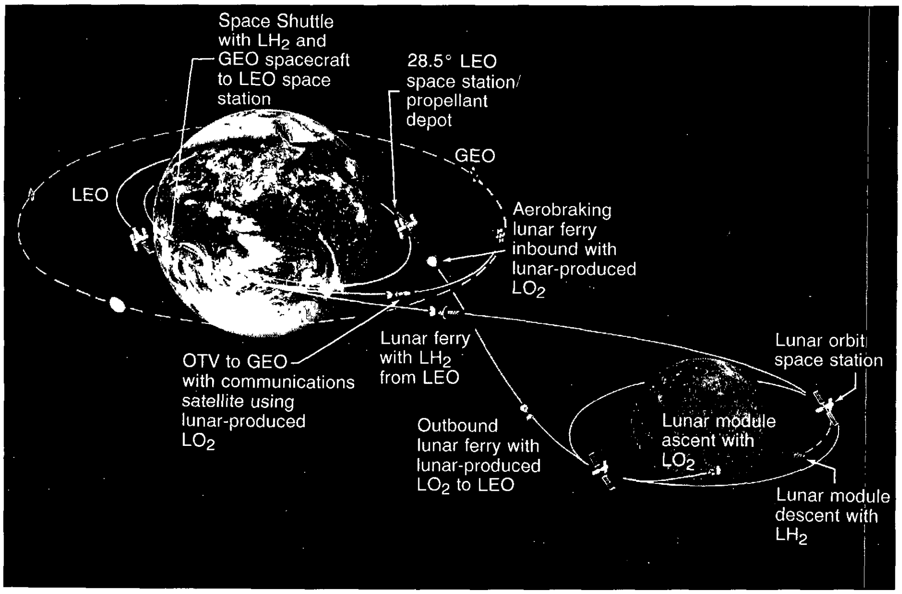


Figure 12

Lunar Oxygen Delivery Orbits and Missions

in orbit, they are recovered and the liquid oxygen is transferred to an aerobraked lunar ferry (shown in figure 15), which delivers it to low Earth orbit. This lunar ferry returns to lunar orbit, bringing back with it some liquid hydrogen. A lunar module returns the empty tanks to the lunar surface so that they can be reused. This lunar module as well as the lunar ferry is fueled by the liquid oxygen coming from the lunar surface and the liquid hydrogen brought back by the lunar ferry. With the empty tanks now back at the electromagnetic launcher site, the process repeats itself.

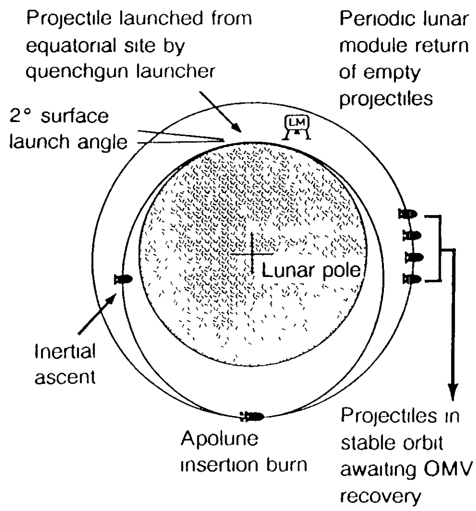


Figure 13

Lunar Launcher Mission

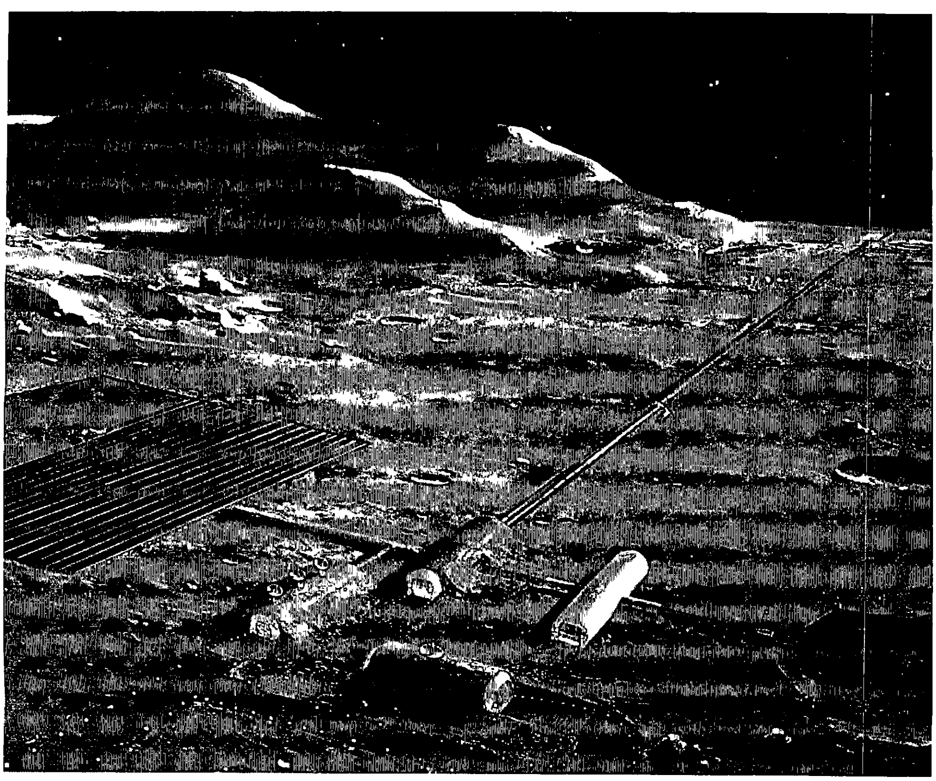


Figure 14

Lunar-Based Superconducting Quenchgun

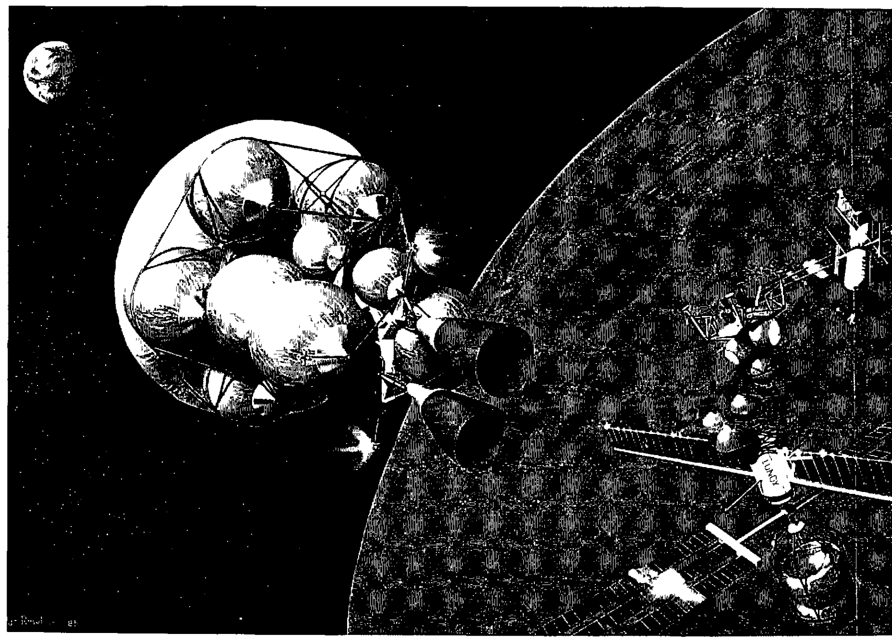


Figure 15

Aerobraked Lunar Ferry
Artist: Pat Rawlings

Electromagnetic Launcher History

The first reported effort to construct and test an electromagnetic launcher was that of Professor Kristian Birkeland at the University of Oslo in 1901 (Egeland and Leer 1986). He received the first world patent for an electromagnetic gun and formed a company, "Birkeland's Firearms," to research and produce them. His largest gun, constructed in 1902, launched 10-kg iron projectiles. The barrel was 10 meters long with a bore of 6.5 centimeters and achieved projectile velocities of 80 to 100 meters per second. He envisioned building guns that would have ranges of 100 to 1000 km. He abandoned his efforts due to a lack of funds and his realization that there were no available pulsed power sources to operate his guns. This would continue to be the case for the next 70 years.

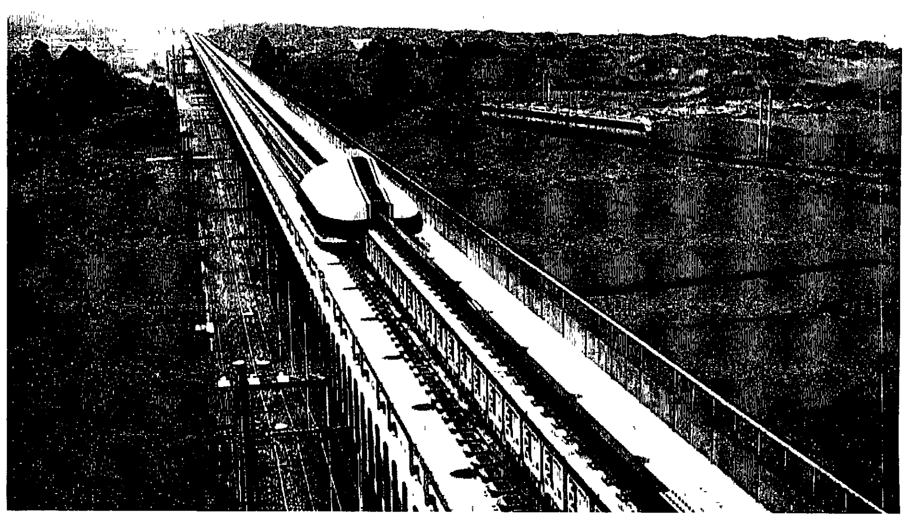
The next reported efforts were made by Professor Edwin F. Northrup at Princeton University in the 1930s (Northrup 1937). He constructed a number of electromagnetic launchers in the early 1930s. His launchers were linear three-phase induction motors (like their rotary counterparts), the same type as Birkeland's guns. He envisioned an ideal electromagnetic launcher in which only a small part of the barrel would be energized at any one time and the energized part would be synchronized with the passage of the projectile, thus minimizing heat losses and being more efficient. This idea required fast high-power opening and closing switches, which did not exist at that time. But the idea would later be used in the mass driver and other launcher designs (coilguns) of the 1970s. He also recognized the effect of magnetic levitation on the projectile; this magnetic force capable of centering the projectile would eliminate friction between the projectile and the barrel. This effect would also be used in the 1970s, with modifications, in the magnetically levitated (maglev) high-speed ground transportation vehicles.

As a variation on Jules Verne's approach, Northrup proposed using an electromagnetic launcher on the Earth to send a capsule with two people onboard on a trip around the Moon. In his book this was to have taken place in the early 1960s and under the condition of a race with Russia to get to the Moon first.

During World War II, several efforts were made to use electromagnetic launch technology. In Germany, at Peenemünde in 1943, an electric catapult for launching V-2 rockets was unsuccessfully tested. In Japan, electromagnetic launchers were studied for use as antiaircraft guns, but they were never constructed. In the United States, the Westinghouse Electric Corporation built a catapult (known as the Electropult) for the Navy to launch airplanes. The catapult wasn't completed until after the war, but it successfully launched airplanes such as the B-25. This catapult lost out to the steam catapult which was being developed at that time for use onboard aircraft carriers. In the late 1940s, electromagnetic launchers were still in their infancy and were still using the inefficient linear induction motor design instead of the more efficient linear synchronous motor design that would be used in the 1980s.

For the next 20 years, electro-magnetic launcher technology lay dormant except for a few efforts in building railguns and a small coilgun built by Thom and Norwood at the NASA Langley Research Center in 1961. Their brush-commutated coilgun was a linear synchronous motor (unlike all previous electromagnetic launchers). It was proposed for use as a lunar launcher in support of a large base on the Moon. However, Thom and Norwood's work would lie unknown until after the concept of mass drivers emerged in the late 1970s.

In the late 1960s and early 1970s, electromagnetic launcher technology was being developed for high-speed ground transportation by the United States, Japan, and Germany (Kolm and Thornton 1973). The first repulsively levitated synchronous high-speed transportation system (known as the Magneplane) was developed and tested at 1/25 scale in the early 1970s as a joint effort by MIT's Francis Bitter National Magnet Laboratory and Raytheon. This concept has been adopted by both the German and the Japanese maglev group, who are continuing their efforts, but U.S. support for maglev research was terminated in 1975. A Japanese maglev system, which rides on a cushion of air, has reached test speeds of 520 kilometers per hour (325 mph).



Maglev Test Track in Japan

An offshoot of this maglev research resulted in the concept of the mass driver by Professor Gerard K. O'Neill of Princeton University in 1974. It was based on features of the Magneplane, like magnetic levitation and superconducting armature coils, but the drive circuit was based on the resonant transfer of energy from capacitors rather than on a three-phase power supply. The mass driver was proposed as a means for launching raw materials (payloads of 1-10 kg size at launch rates of 1-10 per second) from a lunar base to a construction site in space. The mass driver was studied extensively for missions of this type, during three NASA Ames summer studies in 1975, 1976, and 1977 (Billingham, Gilbreath, and O'Leary 1979) and subsequently at MIT and Princeton University (Snow 1982). The first lunar launcher proof-of-concept model was constructed in 1977 by a group of students at the MIT Francis Bitter National Magnet Laboratory; it is shown in figure 16.

The energy storage capacitors in the mass driver dominate its mass and cost. And, because capacitors have a low energy density, they are especially unsuitable for an electromagnetic launcher of lunar oxygen, facing the requirements of a larger payload mass at a lower launch rate.

Looking for an alternative way to launch nuclear waste from the surface of the Earth, Henry Kolm in 1978 developed the idea of the superconducting quenchgun (Kolm

Figure 16

Mass Driver I During Construction

While Gerard K. O'Neill, a Princeton physics professor, was on sabbatical as the Hunsaker Professor of Aeronautics at MIT in 1976-77, he and Henry Kolm, one of the cofounders of the Francis Bitter National Magnet Laboratory, led a team of students in building Mass Driver I. Shown here are Bill Snow, Kevin Fine, Jonah Garbus, O'Neill, Kolm, and Eric Drexler.

In 1977 it was widely believed that a highly advanced mass driver, using the most sophisticated materials and design, could achieve at best 50 gravities of acceleration. However, even this primitive model, built from about $3000 worth of scrounged equipment, demonstrated an acceleration of over 30 g's.

Courtesy of Space Studies Institute

et al. 1979, Graneau 1980). The quenchgun is analogous to the Carnot engine in thermodynamics—the ideal launcher capable of achieving the maximum theoretically possible efficiency. It eliminates the need for energy storage capacitors. Quenchguns store the entire launch energy in the superconducting barrel coils and transfer it to the projectile almost without loss.

The quenchgun concept was not pursued in 1978 because it was considered impractical for any tactical terrestrial applications of interest at the time. High-temperature superconductors or better refrigerators would be required. However, the quenchgun is practical, even with existing low-temperature superconductors, on the cold lunar surface. A proof-of-concept model of the quenchgun was built and successfully tested in 1985 using normal conductors and silicon-controlled rectifier (SCR) switches (Snow and Mongeau 1985).

Electromagnetic Launcher Coilgun Principles

Coilguns achieve acceleration by the Lorentz force exerted by one or more current-carrying barrel coils on one or more current-carrying projectile coils. The barrel and projectile coils can be coaxial or coplanar, as long as they are inductively coupled to each other. The thrust generated is simply the product of the two coil currents times a proportionality constant. This constant is the mutual inductance gradient between the projectile coil and the barrel coil. The mutual inductance gradient for a coilgun is typically about 100 times as large as that for a railgun. As a result, the coilgun generates 100 times more thrust for a given heat loss.

This large thrust is generated only when the two coils are in close proximity to each other. Therefore, coilguns require that the barrel coil current must be synchronized with the passing projectile. When normal conductors are used, this current must be supplied by a pulsed power source to minimize energy loss due to conductor heating.

In the mass driver, the synchronization was accomplished by triggering the resonant capacitor discharge to coincide with the passage of the projectile. Capacitors unfortunately have too low an energy density to be practical, and it becomes necessary to use inductive energy storage when megajoules of launch energy are needed.

Unfortunately it is difficult to commutate (turn the current in a coil on or off) inductively stored energy. This can be accomplished by the use of brushes located on the projectile to synchronize the barrel current with that in the projectile. However, brushes are not suited to the large energies and vacuum environment of the lunar launcher mission, and the wear they would cause is unacceptable in such a mission. The only reasonable option for this mission is the superconducting quenchgun, which is capable of storing the entire launch energy in its barrel without loss and of commutating it synchronously without brushes.

Quenchgun Principles

The quenchgun consists of a superconducting solenoid barrel divided up into a number of short, current-carrying barrel coils. Each of the barrel coils is open-circuited (after the barrel coil current has been de-induced) at the instant the projectile coil passes through it. When the projectile reaches the muzzle, nearly all of the energy initially stored in the barrel will have been transferred to the projectile in the form of kinetic energy.

The unique feature of the quenchgun is the superconducting barrel coils. Ordinary conductors cannot store the entire launch energy in the barrel coils very efficiently for more than 1 second. Superconductors, on the other hand, can store this launch energy without loss for an indefinite period of time. Because of this feature, the superconducting quenchgun can be charged up between firings. Thus the superconducting barrel requires only 1/10 000 the power required by a non-superconducting barrel.

To provide the very high pulse power needed in a non-superconducting barrel, the source would have to be some sort of rotating machinery (with bearings that would wear), such as a flywheel/pulsed alternator. The power for a superconducting barrel can instead be derived from a much simpler and smaller solar or nuclear source. This is the key feature that makes the superconducting quenchgun a much more practical device for lunar launching than any other electromagnetic launcher.

The operation of a superconducting quenchgun is illustrated in figure 17. It consists simply of a row of short coaxial superconducting barrel coils, with an oversized injection coil at the breech. The projectile coil is at rest in the breech, as shown in the first of the three diagrams. It does not need to be superconducting, as long as its characteristic time constant is longer than the launch time. This time constant increases with size, and at the size proposed aluminum or beryllium alloys meet the requirement if they are precooled to about 80 K. To initiate the launch, it is necessary merely to quench the injection coil, as indicated in the second diagram. This induces a current in the projectile coil, which will persist for more than the duration of the launch. The projectile is now sucked into the quenchgun, as shown in the third diagram. As the projectile reaches the first barrel coil, it induces a current zero (by what is called motion-induced commutation), and the superconductivity of the first coil must be quenched so as to prevent current from being re-induced in the barrel coil as the projectile coil passes through it. If the superconductivity of the barrel coil is not quenched, the re-induced current in it will pull the projectile backward and reduce its acceleration force.

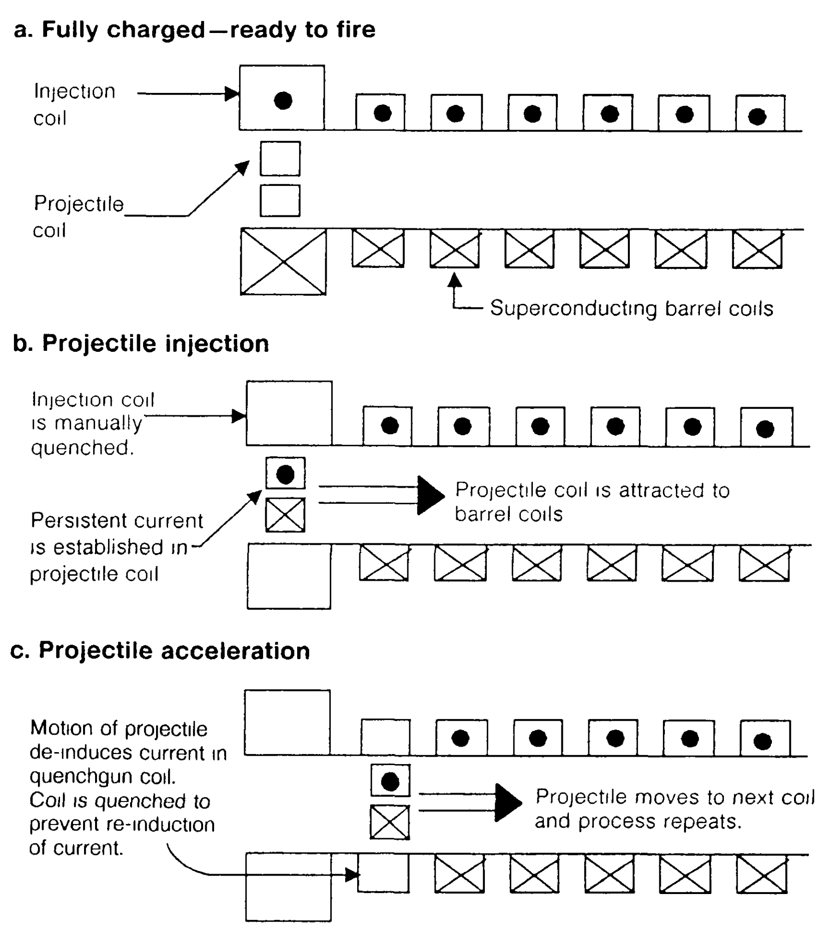


Figure 17

Principles of Quenchgun Operation

Quenching can be accomplished by simply exposing a small portion of the barrel coil winding to radial flux from the approaching projectile coil, making sure that the critical magnetic field in this portion is exceeded. An equally simple method of quenching would be to have the heat induced by the moving projectile coil exceed the critical temperature at the prevailing magnetic field. The important factor is the absence of current at the instant of quench, and therefore the absence of energy dissipation. Each barrel coil is quenched in succession as the projectile coil approaches, and the projectile thus acquires nearly all of the energy initially stored in the barrel.

As shown in figure 18, all of the barrel coils are charged in series to minimize the required charging current and the number of connecting leads. After the barrel is charged, the individual barrel coils are disconnected from this series connection just before launch. They can be disconnected simply by turning on the rhermally activated superconducting shunt switches across the barrel turns and turning off the swıtches connecting the turns ın serıes.

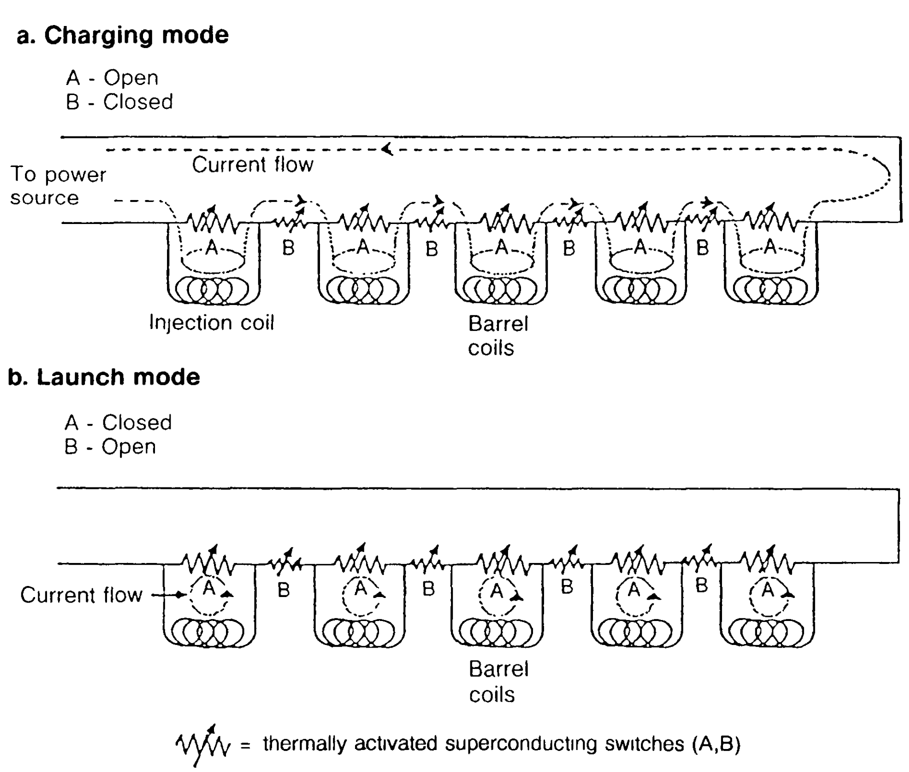


Figure 18

Quenchgun Charging and Launch Modes

A Lunar Superconducting Quenchgun Design

The Quenchgun Barrel

We now present a preliminary reference design to show the main features and components of a lunar-based superconducting quenchgun for use in launching 1-ton containers of liquid oxygen, one every 2 hours. At this rate nearly 4400 tons of liquid oxygen would be launched into low lunar orbit in a year. This is only one of several possible plans for launching lunar oxygen tanks from the lunar surface with a quenchgun. Figure 19 shows the basic features of the barrel.

The quenchgun consists of a cold inner section connected by slinky springs to a warm outer section. The cold inner section consists of the barrel coil modules, each about 1 meter in diameter and 0.5 m long, separated by flanges between

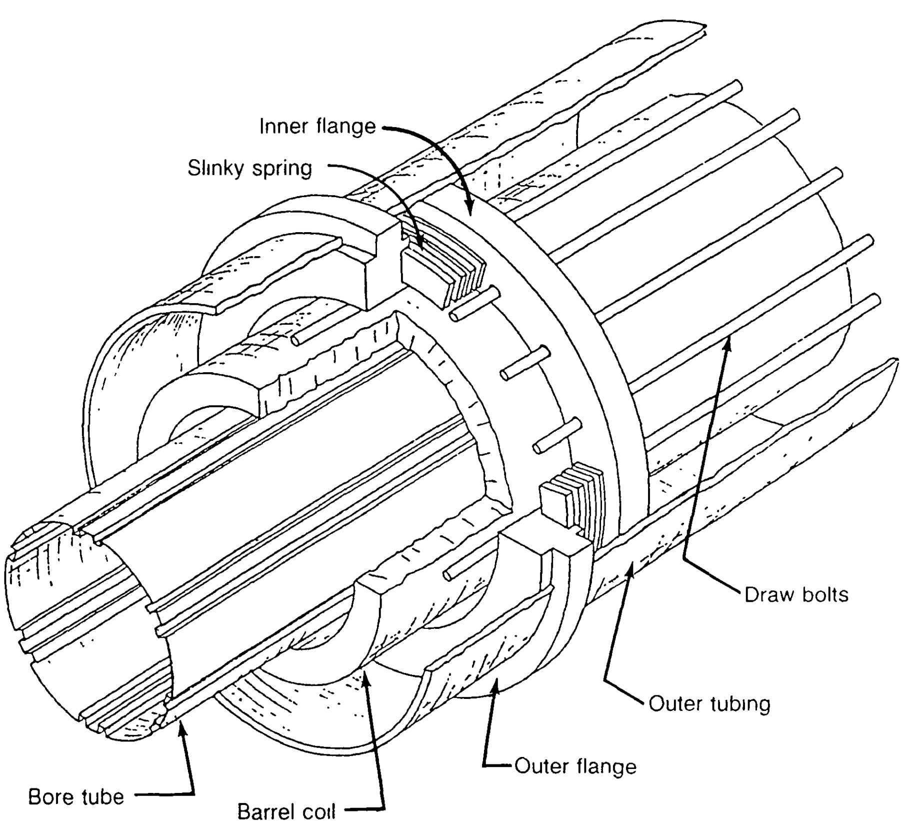


Figure 19

Quenchgun Barrel Module

neighboring coils and compressed by 16 draw bolts which pass through holes in the flanges. Cooling is provided by a forced flow system of supercritical helium using small-diameter stainless steel tubing, which is not shown.

Superinsulation is used as a radiation heat shield between the warm outer section and the cold inner section.

The cold inner section is connected to the warm outer section by slinky springs as shown; they are made of fiber-reinforced composite (to avoid high induced voltages). These springs provide a very long heat conduction path and at the same time permit the inner cold section to recoil. During the instant of recoil, the inner flanges thus transmit the very strong axial forces directly to the outer flanges through the completely compressed slinky springs, causing a temporarily high heat leak. When the barrel is not undergoing recoil, however, the heat leak through the slinky springs is very low, approximately 1 watt per ton of suspended cold system mass. Any rigid suspension system capable of withstanding the recoil force would involve about 100 times this heat leak.

The only metal components of the entire launcher are the superconducting coils, the draw bolts, and the stainless steel cooling tubes for the supercritical helium refrigeration system. Inner tube, outer tube, and all flanges are reinforced composite. Metal cannot be used too near the barrel coils because it would carry very high induced circumferential currents.

The Carriage and the Liquid Oxygen Tank

The projectile consists of two major components, as shown in figure 20. One is the tank that contains the liquid oxygen which is to be delivered to low lunar orbit. This tank has an apolune kick motor on one end which is used to circularize the orbit. Orientation of the tank for proper altitude control is accomplished by spin stabilization. Since this tank must be returned to the lunar surface for reuse, its mass must be minimized. It only needs to be strong enough to handle loads experienced after launch.

To withstand the high acceleration force placed on it during launch, it rests inside a carriage that can take this force. This carriage contains the projectile (armature) coil made from aluminum or beryllium, and stress containment is provided by a graphite-reinforced hoop. Since the carriage is decelerated at the launcher site, it never leaves the Moon and thereby improves the efficiency of delivering oxygen.

The Carriage Decelerating Barrel

For deceleration, the barrel coils are connected in series and no commutation is required. The decelerating barrel coils are energized with a suitable current level in the opposing direction. As the projectile coil enters the decelerator, both the barrel coil current and the projectile coil current increase progressively, until the carriage is brought to rest and clamped mechanically at its stopping position. If not clamped, it would simply rebound. The projectile coil current is then allowed to decay. The superconducting barrel coil in the decelerator can be connected to the accelerating barrel coils so that a fraction of the braking energy is reused for the next launch.

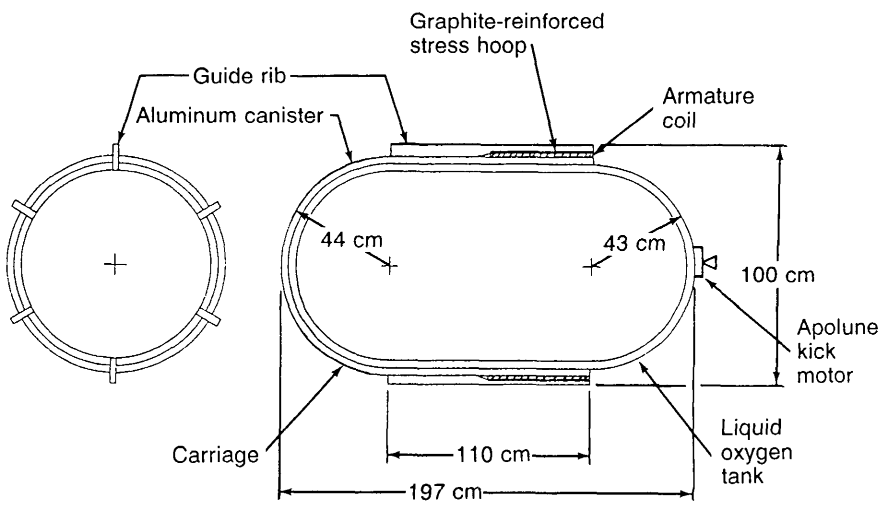


Figure 20

Quenchgun Carriage and Liquid Oxygen Tank

Carriage Retrieval

A mechanical retrieval mechanism is used to return the carriage to the breech after a launch. One possible retrieval mechanism is a self-propelled "mole" powered through an umbilical cable. It normally rests in a dead siding behind the carriage/tank insertion position at the breech. To retrieve the carriage, it propels itself to the decelerating section, connects mechanically to the carriage, and pulls the carriage back to the breech either by itself or by retracting a cable attached back at the breech.

System Description

The system design is based on launching a 1-ton payload of liquid oxygen every 2 hours into low lunar orbit. A block diagram of the components of a superconducting quenchgun is shown in figure 21. The overall use of the superconducting quenchgun in supplying liquid oxygen from the Moon is shown in figure 22. And a summary of the superconducting quenchgun specifications for this reference design is presented in table 10.

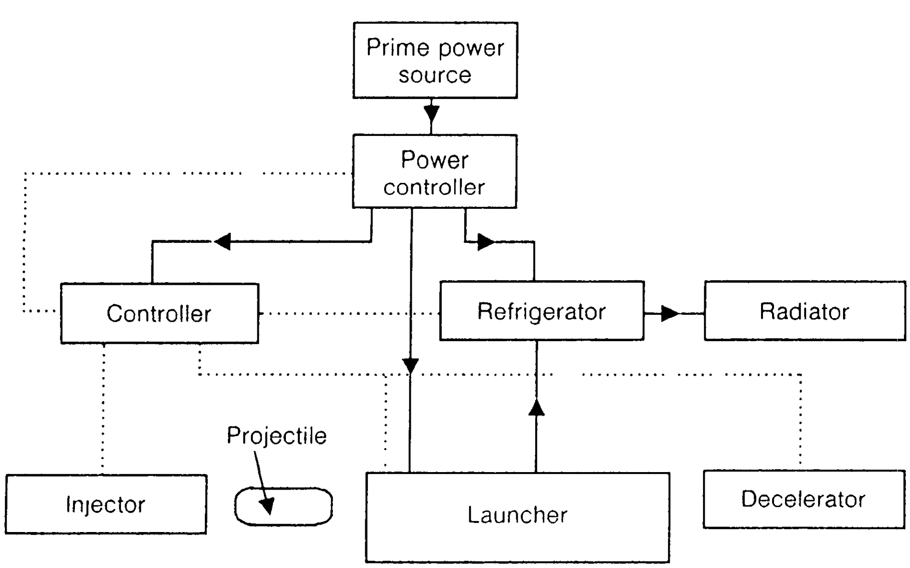


Figure 21

Quenchgun Components

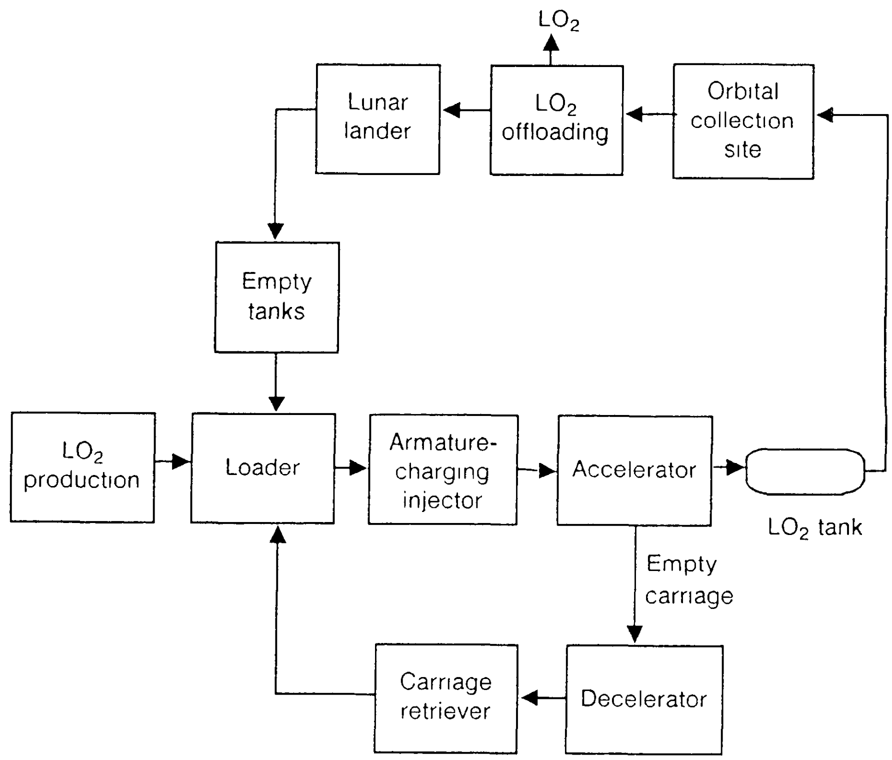


Figure 22

Quenchgun Operation

TABLE 10. *Superconducting Quenchgun Specifications*

Launch performance	
Projectile mass	1500 kg
Payload (oxygen) mass	1000 kg
Velocity	1700 m/sec
Length	150 m
Acceleration	983 *g*'s
Barrel energy	2170 MJ
Launch time	0.18 sec
Force	14.5 MN
Decelerator length	50 m
Projectile (armature coil)	
Coil inner radius	43 cm
Coil outer radius	47 cm
Width	48 cm
Current density	30 kA/cm^2
Quenchgun (barrel coil)	
Coil inner radius	52 cm
Coil outer radius	56 cm
Current density	14 kA/cm^2
System	
Launcher mass	250 metric tons
Decelerator mass	83 metric tons
Power required	350 kW for 1 launch/2 hr

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Tethers

Andrew H. Cutler and Joseph A. Carroll

A tether of sufficient strength, capable of being lengthened or shortened and having appropriate apparatuses for capturing and releasing bodies at its ends, may be useful in propulsion applications. For example, a tether could allow rendezvous between spacecraft in substantially different orbits without using propellant. A tether could also allow co-orbiting spacecraft to exchange momentum and separate. Thus, a reentering spacecraft (such as the Shuttle) could give its momentum to one remaining on orbit (such as the space station). Similarly, a tether facility could gain momentum from a high I_{sp}/low thrust mechanism (which could be an electrodynamic tether) and transfer that momentum by means of a tether to payloads headed for many different orbits. Such a facility would, in effect, combine high I_{sp} with high thrust, although only briefly. An electrodynamic tether could propel a satellite from its launch inclination to a higher or lower inclination. Tethers could also allow samples to be taken from bodies such as the Moon. Three types of tether operations are illustrated in figure 23.

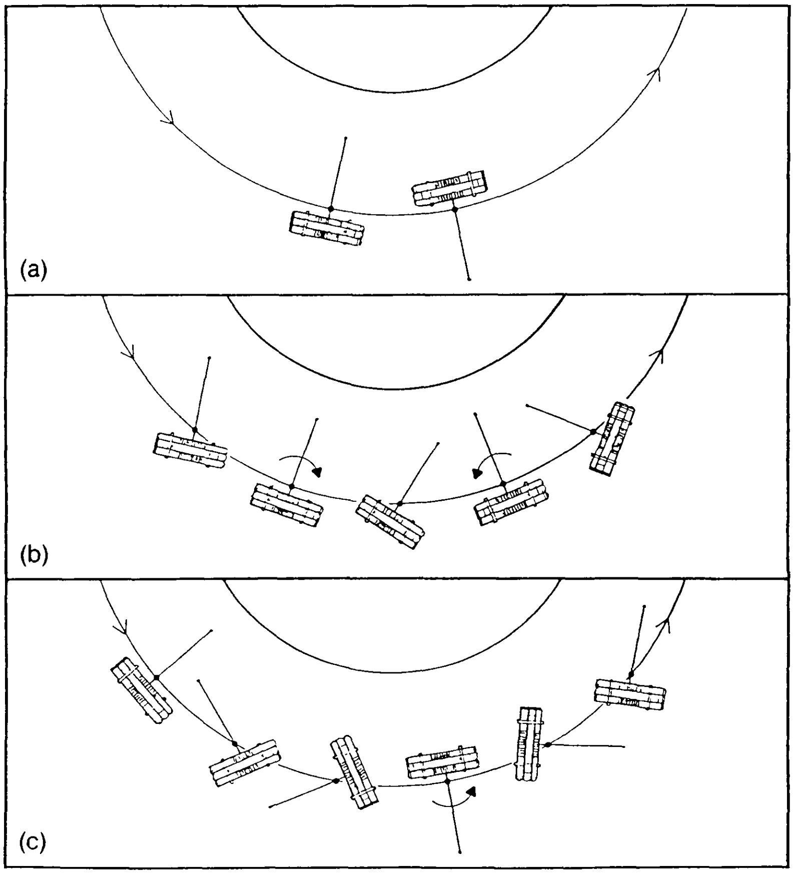

Figure 23

Three Modes of Tether Operation

a. Hanging, with the tether stably pointing toward or away from a massive object.

b. Swinging about a stable position, with the tether pointing toward a massive object.

c. Spinning in the orbital plane and in the same direction as the orbiting system (posigrade).

Whether hanging, swinging, or spinning, the tether works by releasing its payload at a favorable point in its motion. The center of gravity of the system is indicated by a dot along the tether and is shown orbiting about a massive object. The size of the platform and the distance of the center of gravity from the platform have been exaggerated for clarity.

Taken from Martin O. Stern, 1988, Advanced Propulsion for LEO-Moon Transport, Progress Report on work performed under NASA grant 9-186 (James R. Arnold, Principal Investigator), Calif. Space Inst., Univ. of Calif., San Diego, June.

Electrically conducting tethers will couple to the Earth's magnetic field. In low Earth orbit (LEO) there is sufficient plasma density to allow large currents to flow through the tether and close the loop efficiently through the plasma. The interaction between the current and the magnetic field produces a force that propels the tether. Such a tether can convert electrical energy (from a photovoltaic array, for example) to thrust with high efficiency (2-8 kW/N), without expending propellant. Vehicles with a hanging electrodynamic tether propulsion system could go from any arbitrary low Earth orbit to any other arbitrary low Earth orbit in a few months.

Tether Characteristics

A tether is a long tensile structure in space. In the applications discussed here, it is generally 10 to 200 kilometers long and is under a tension of hundreds to a few tens of thousands of newtons. There are usually objects at the ends of the tether which are more massive than the tether itself. An introductory handbook on tethers is available (Carroll 1985), and many prospective tether applications are described by Carroll (1986).

A tether in orbit will experience a gravity gradient force orienting it toward the local vertical. In LEO this force is about 4×10^{-4} gravities per kilometer from the center of mass of the tethered system. The tether may oscillate about the local vertical. These oscillations can be broken into components parallel and perpendicular to the plane of orbital motion. The out-of-plane potential function is symmetrical with respect to position and velocity. The in-plane potential function is not symmetrical. Tension is greater for a swing in the direction of orbital motion (posigrade) than it is for a swing contrary to the direction of orbital motion (retrograde).

Since the tether exerts a net force on the mass at either end of it, the path the mass follows is not a free orbit. If an object is released by a hanging tether of length ℓ, the orbits of the two end masses will be separated by ℓ at that point and by about 7 ℓ half an orbit later. If release is from the top or bottom of the swing of a widely swinging tether, the initial separation will again be ℓ and the separation half an orbit later will be about 14 ℓ.

A current-carrying tether in orbit around a body with a significant magnetic field (such as Earth or Jupiter, but not the Moon or Mars) experiences a JxB magnetic force perpendicular to both the tether and the magnetic field. (This is the force that results when an electric current of density J is passed through a magnetic field of inductance B.) The tether will usually be held close to the local vertical by gravity gradient forces, so the direction of thrust is not arbitrarily selectable and it will generally have an out-of-plane component which varies with time. Appropriate current control strategies will be necessary to allow use of electrodynamic tethers as efficient thrusters. Reasonable estimates of power per thrust are 2 to 8 kilowatts per newton, depending on the orbital inclination. For Earth, the lower power consumption is at high inclinations, where fewer lines of the magnetic field are crossed.

One would expect the best electrodynamic tether material to be that with the highest specific conductivity—lithium or sodium. However, these high specific conductivity materials are not very dense and therefore have a low areal conductivity. That is, wire made of lithium or sodium is larger in diameter than wire with the same conductivity but made of a more dense material, such as copper. Typical electrodynamic tethers operating at kilovolt potentials must be insulated against current loss. Because insulation is of roughly the same thickness whether it is applied to small- or large-diameter wire, the less dense conducting wires require more massive insulation. Tradeoffs between high specific conductivity and high areal conductivity must therefore be studied for each application.

Tether materials are subject to degradation in the space environment. High-strength plastics will be degraded by ultraviolet and ionizing radiation and by atomic oxygen in LEO. The effects of these degradational influences and the utility of protective coatings must be studied.

Although tethers are typically quite thin, their great length gives them a large impact area. Thus, they have a significant chance of failure due to micrometeoroid impact. This chance is conservatively estimated to be 1 cut per kilometer-year of exposure of a heavily loaded 1-millimeter-thick tether in LEO. The risk of system failure can be reduced by using multiple independent strands or a tape. While a tape would be hit more often, a micrometeoroid would only punch a hole in it and not sever it, as it might a single strand. However, additional insulation would be required for multiple strands or a tape.

Tether Propulsion

Basics

The simplest operation with a tether is to raise or lower an object and release it from a hanging tether. Since a tethered object is not in a free orbit (the tether exerts a net force on it), this method can be used to change velocity without using rocketry. Even in this nominally hanging case, there will be some libration of the tether. By controlling the tether tension and thus mechanically pumping energy into these librations (like a child pumping a swing), the tether can be made to swing.

The characteristic velocity, V_C, of a tether can be defined as the square root of its specific strength (that is, its tensile strength divided by its density):

$$V_C = \sqrt{\frac{s}{\rho}}$$

where s is the tensile strength (that is, force per unit area which the tether can withstand without breaking) and ρ is the density. Typical numbers for reasonable engineering systems are 350 meters/second for steel, 700 m/sec for Kevlar, and 1000 m/sec for high-density polyethylene fibers. These characteristic velocities incorporate an adequate safety factor to account for manufacturing variations in the material and for degradation in use. The higher the effective V_C, the lower the tether mass for a given operation.

The characteristic velocity just defined is for a spinning tether. The effective characteristic velocity depends on the type of tether operation. To convert V_C for a spinning tether to V_C for some other operation, multiply by the factor given below.

Hanging $\sqrt{\frac{4}{3}}$

Swinging $\sqrt{\frac{3}{2}}$

Winching $\sqrt{2}$

Thus, to impart a velocity change much less than V_C to a unit payload mass, the ratios of required tether mass to that of a spinning tether are as follows:

Hanging : Spinning $\frac{3}{4}$: 1

Swinging : Spinning $\frac{2}{3}$: 1

Winching : Spinning $\frac{1}{2}$: 1

The velocity that a tether imparts to a payload depends on the orbital velocity of the tether, the speed at which it is swinging or spinning, and the length of the tether. The tether can be lighter than its tip mass if the desired velocity change is much lower than the characteristic velocity. As the desired velocity approaches V_C, the mass of the tether becomes appreciable. As a propulsion system, a tether is more efficient than a rocket for small velocity changes (that is, it weighs less than the rocket propellant necessary), but it is less efficient for large changes. Thus, a tether will not be cost-effective in comparison with a rocket if a large velocity change must be made and the tether is used only once. If the tether can be used for more than one operation, the velocity at which the tether is more mass-efficient than a rocket becomes larger. Using a tether for part of any required velocity change will always be beneficial if the momentum has different costs (or values) at the two ends of the tether.

Propulsion via Momentum Transfer

There are many potential propulsive uses of tethers. Rockets from Earth, orbital maneuvering vehicles (OMVs), and orbital transfer vehicles (OTVs) could be boosted and deboosted with tethers to reduce their rocket-supplied velocity changes by hundreds of meters per second. A permanent facility in Earth orbit would serve as a momentum storage bank. (See figure 24.) It could lend momentum to a vehicle launched from Earth; by so doing, its own orbit would be lowered. It could regain momentum by releasing a spacecraft which is returning to Earth; by doing this, the

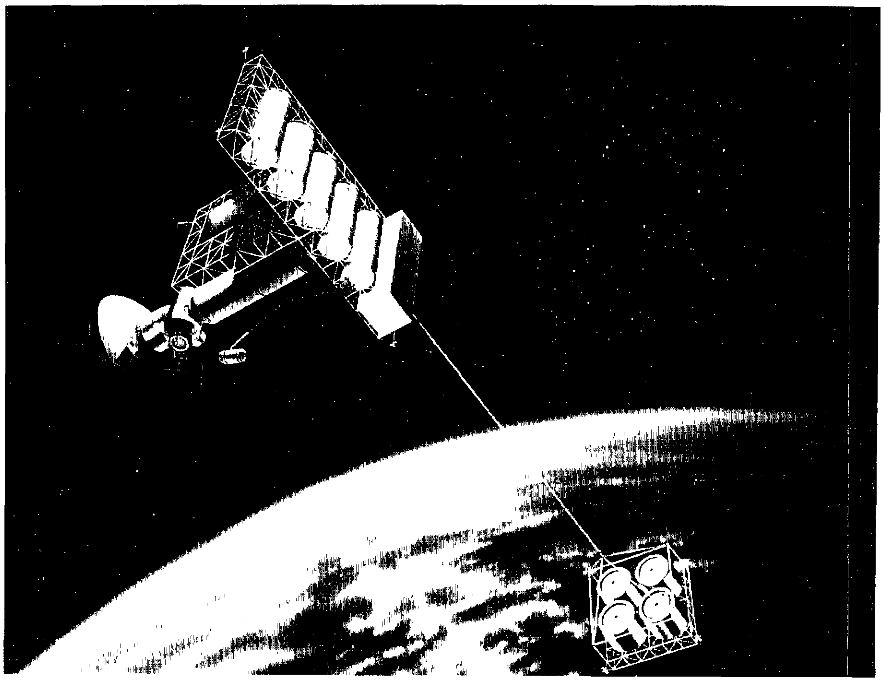

Figure 24

Concept for a Spinning Tether System in Low Earth Orbit

The tether facility rotates around the Earth in an eccentric orbit such that the end of the 100-km-long tether can rendezvous with a payload in orbit with the space station. The payload is then swung on the tether to the release point, where it receives additional velocity toward the Moon. The transfer of momentum to the payload reduces the momentum of the tether facility and thus lowers its orbit. This momentum can be recovered by the facility if it catches and slows a payload returning from the Moon to low Earth orbit.

Taken from Eagle Engineering, Inc., 1988, LEO/Moon Transport: Advanced Propulsion Concepts Assessment, EEI Report 88-217, Oct. 26.

Artist: John Michael Stovall

facility's orbit would be raised. Space-based vehicles (OMVs and OTVs) could also benefit. If the tether propelling it broke, the OMV or OTV could rely on built-in propulsive capability to return to the space station and try again. This operation is described in more detail in the appendix.

The greater the tether facility mass, the smaller the effect on its orbit produced by the momentum loaned to it or borrowed from it. Thus, accumulating mass would be desirable and would give the system more flexibility. Mass could be accumulated at the facility by collecting massive disposable items, such as external tanks. Tether operations that provide velocity changes of up to 1000 m/sec are feasible using currently available materials. Larger velocity changes are possible, but they require tapered tethers more massive than the payloads boosted.

The net impulse invested in the OMVs and OTVs, in their payloads, and in the propellant they consume must be made up. It could be made up by a second tether at the same orbiting facility. This second tether would be an electrodynamic tether with a solar power source. It would slowly convert solar-generated electricity to thrust. This tether thruster would work continuously at low thrust (high specific impulse) to raise the facility's orbit. Periodically, the orbit would suddenly be lowered when the other tether—the one providing high thrust—accelerated a payload.

As this thruster would not travel with the payloads or undergo significant velocity changes, it could have a relatively large inert mass, compared to that permissible on an OTV. The expense of transporting the thruster mass into orbit would quickly be paid for in vehicle propellant savings. Other advantages to such a thruster are that it would be accessible for maintenance and repair at all times and that its power supply would not be repeatedly exposed to radiation trapped in the Van Allen belt. Its duty cycle would have to be high enough to provide impulse at the rate that OMV and OTV launches used it up. The mass of the tether facility would damp out small variations in orbital energy due to tethered boosts and erratic thruster use.

This tether system could be located at the space station. If so, tethered rendezvous, boost, and deboost would have an impact on space station design. These operations would exert net forces on the space station. Using ambitious Shuttle capture schemes, these forces would be much larger than the forces from any other operation. Solar cell arrays and other extended structures would be particularly sensitive to such forces.

Electrodynamic Tether Propulsion

A vehicle driven by an electrodynamic tether is capable of changing the inclination of its low Earth orbit in a month or so. (See figure 25.) Such a vehicle would make all satellites in low Earth orbit serviceable from a space station orbiting at a 28.5-degree inclination. Payloads destined for high-inclination orbits could be launched into 28.5-degree orbit (or any other orbit easily accessible from the launch site) and then delivered by an orbital maneuvering vehicle to the higher inclination. Spacecraft could also be delivered to an inclination lower than 28.5 degrees. Delivery to lower inclinations would reduce the amount of fuel required for orbital plane changes in going to geosynchronous equatorial orbit. Instruments and experiments (biological or other) that are affected by exposure to the South Atlantic anomaly could be placed in orbits with inclinations low enough to greatly reduce overall radiation exposure.

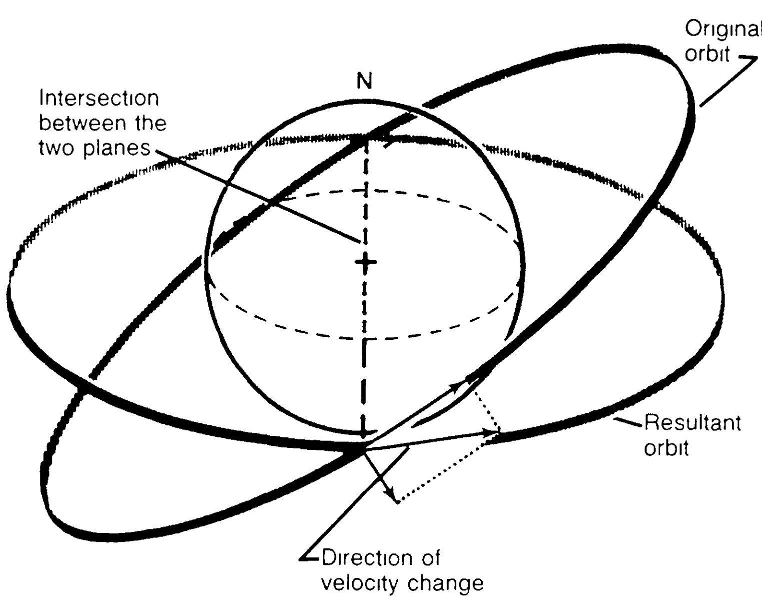

Figure 25

Orbital Plane Change

The angle between the plane of a spacecraft's orbit and some reference plane, such as the equator, is called its inclination. A spacecraft can change its inclination by firing its engines while pointed at an angle to the plane of the spacecraft's current orbit. As shown in the figure, the new orbit plane will be the resultant of the vector addition of the original velocity and the velocity change accomplished with the engine firing. Plane changes and orbit altitude changes are often accomplished in the same maneuver. These orbit changes can be accomplished by low thrust propulsion or by tether momentum management techniques as well as by conventional rocketry.

Taken from AC Electronics Division, General Motors Corp., 1969, Introduction to Orbital Mechanics and Rendezvous Techniques, Text 2, prepared under NASA contract 9-497, Nov.

Because its electrodynamic tether would need a relatively dense plasma to close the current loop, such an OMV would be limited to low Earth orbits. With currently projected solar or nuclear power sources, an electrodynamic OMV could move a payload heavier than itself from a 28.5-degree orbit to a 104-degree orbit in a few months. Thus, all payloads for high-inclination orbits could be launched due east to maximize mass on orbit and then be moved to their final destination. This two-step method could double the Shuttle's capacity to deploy payloads destined for high-inclination orbits. This method would also allow any low-Earth-orbit satellite to be returned to the space station for servicing and then be redeployed.

An alternative means of turning spacecraft power into orbital changes is by mechanically pumping a tethered system in resonance with its orbital period (to couple to orbital eccentricity or to nonspherical terms in the gravitational field). This means would be less effective than an electrodynamic tether at low altitudes, but it could be superior at altitudes from 3000 to 8000 km. Accelerations at these altitudes are less than 1/20th those achievable in LEO. Above these altitudes, neither mechanical nor electrodynamic tether propulsion is effective.

Planetary Exploration

Sample recovery from celestial bodies is a challenging propulsion problem. Conventional approaches require large, low-specific-impulse propulsion systems to provide enough thrust to land and take off again. Sampling is restricted to a small area because of the difficulty of moving about on the surface of the body. Tethers offer a unique and desirable solution to this problem.

With currently available engineering materials, it is possible to sample from orbit the surface of bodies the size of the Moon and smaller which have no appreciable atmosphere. A long tether would be deployed from an orbiting spacecraft and spun so that its tip touched the body's surface at a relative velocity near 0. Such a vehicle in polar orbit around a celestial body could, in principle, sample any place on the body's surface. A high-specific-impulse, low-thrust propulsion system (which could not land on the body's surface) could be used to accumulate momentum for such sample-boosting operations. Most small bodies on which this operation is practical do not have enough plasma or magnetic field to allow the use of electrodynamic tethers.

A lunar polar orbiting skyhook equipped with ten 200-kg tapered

Kevlar tethers (or ten 50-kg Allied-1000 tethers) could recover about 700 10-kg samples from any desired locations on the lunar surface. Using an electric thruster with a specific impulse of 1000 seconds in conjunction with such a mechanical tether system, the ratio of recovered samples to tethers and propellant is 2.2 : 1 (or 4.3 : 1 for the lighter tethers). Reasonably sized vehicles (5 000-10 000 kg) could return many large samples of material from the Moon or any of the satellites of the outer planets using this technique.

Tether life will be limited by micrometeoroid damage. Using multiple tethers allows missions to be planned on the basis of average tether life, and, if the actual life is shorter than expected, such use allows a rational sampling program to be built.

Conclusions About Tethers

Tethers for rendezvous, boost, and deboost can be deployed and in use by the year 2000. Electrodynamic tether OMVs could be ready by the same year. The only problems may be plasma coupling and plasma conductivity, both of which are to be measured by the Tethered Satellite System experiment in the next 5 years (see fig. 26). A lunar surface sampling tether is possible by 2000 and reasonable by 2010. Tether sampling of other small bodies could follow rapidly.

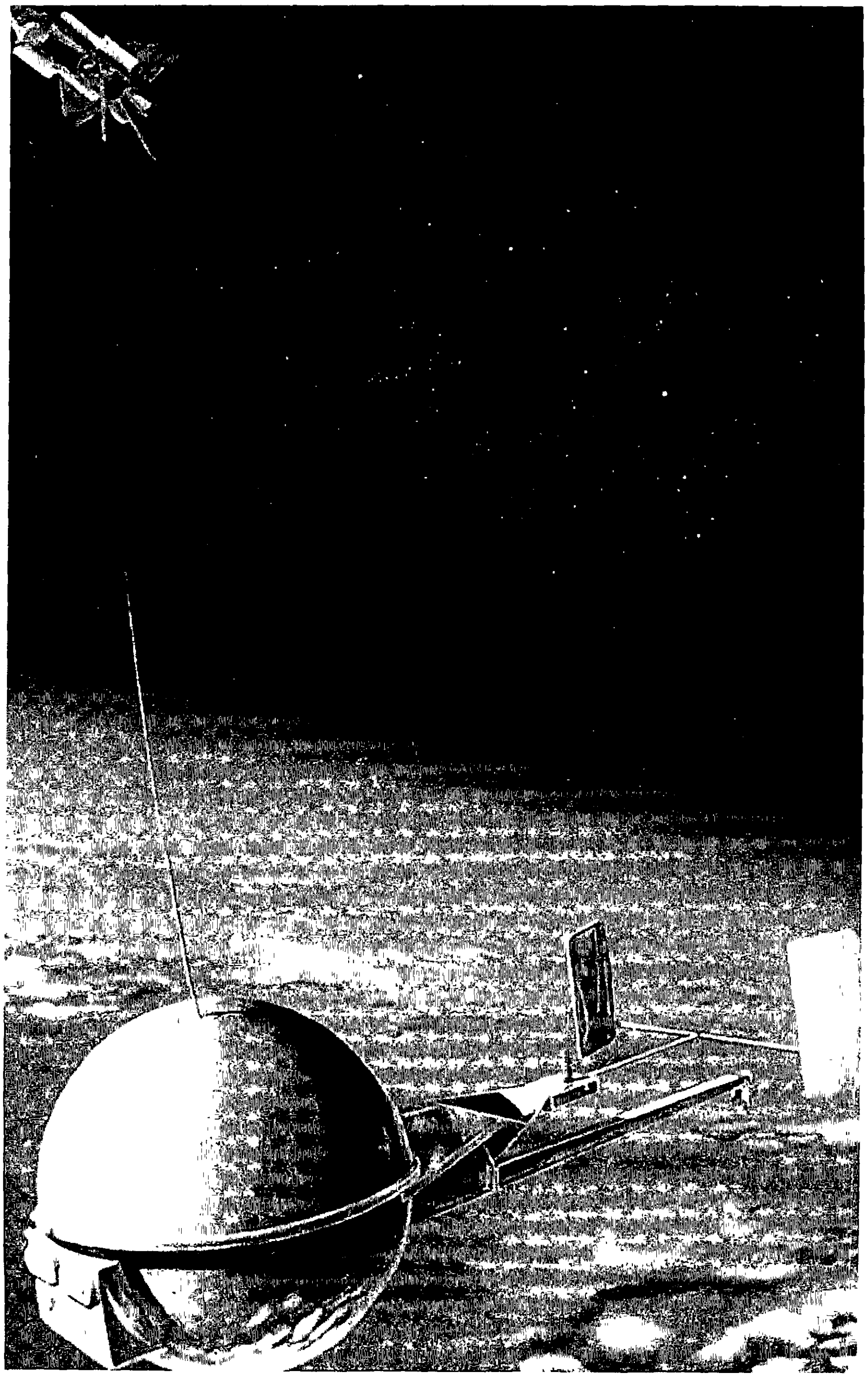

Figure 26

A Tethered Satellite Attached to the Shuttle Orbiter

In this concept, the tethered satellite would be suspended by a cable down as far as 60 miles below the orbital altitude of the orbiter. It would skim through the upper atmosphere, where it could collect gas samples for subsequent analyses.

Use of tethers implies important changes in propulsion for low Earth orbit and elsewhere. Significant efficiencies can be gained using tethers in combination with conventional rockets. Operations will be different, however, and substantial development of operational procedures will be necessary.

There are some specific research questions which will have significant impact on tether systems and which can be addressed now. These questions concern electrical coupling to the space plasma; developing materials with high specific strength; degradation of high-strength polymers in the space environment; micrometeoroid hazards; minimizing wire-plus-insulation mass for materials with high specific conductivity, such as lithium, sodium, and aluminum; tether behavior under perturbations; and tether control laws.

Tethers can do things that rockets and reaction thrusters cannot. They could be a valuable enhancement to the Space Transportation System. Tethers cannot replace rockets and reaction thrusters, but reaction thrusters and rockets cannot replace tethers, either. The combination of tethers and thrusters is much more capable than either one alone.

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Carroll, J. A. 1986. Tether Applications in Space Transportation. Acta Astronautica **13** (April): 165-174.

Appendix

Tethers may be used to mediate Shuttle-to-space-station rendezvous. One part of the space station may be a transportation node, which serves as a service and propellant-transfer area and as a momentum storage device. The Shuttle could be launched into a 73- by 400-kilometer direct-insertion trajectory and rendezvous with a 55-kilometer tether hanging down from the space station at Shuttle apogee. The tether would then be reeled in to recover the Shuttle. After the Shuttle completed its operations at the space station, it could be swung down and back at the end of the 55-kilometer tether.

Such tethered rendezvous between the Shuttle and the space station have a flexibility that contributes to both safety and reliability. The multistrand tether would have an orbital maneuvering vehicle at its tip; both would be deployed and checked before the Shuttle was launched. If the tether broke during the 6 hours between deployment and rendezvous, the OMV could take the Shuttle to the station. If both the tether and the OMV failed, the Shuttle could use its orbital maneuvering system (OMS) to climb to the space station's altitude, provided it carried enough OMS propellant. If it did not, then the Shuttle could abort to a lower orbit and await another OMV, if one was available. The probability that one strand of a tether would be cut by micrometeoroids during a 6-hour period is less than once in 1250 flights for a tether sized to take the required load. The probability that the OMV would fail during this time is also low.

The chances of successful rendezvous are also enhanced by the tether method. If the Shuttle failed to rendezvous with the tether tip, the OMV could be released to rendezvous with the co-orbital Shuttle using free-fall techniques. (In this case, it would be necessary to burn OMS fuel to raise the Shuttle's perigee to about 185 kilometers to prevent reentry.)

Reeling the Shuttle up to the space station by tether would save 6 tons of OMS propellant. It would cost about 1200 pounds of OMS propellant per minute for the Shuttle to hover near the tether tip. So, the quicker the connection is made, the greater the savings in propellant. Lowering the Shuttle by tether to allow it to reenter the atmosphere would save a further 3 tons of OMS propellant and recover more momentum from the Shuttle than was loaned to it. The added momentum would reduce or eliminate the need to make up for space station drag.

Since there are commercial plans to use OMS-type propellant (monomethylhydrazine oxidized by nitrogen tetroxide) for integral rockets to boost satellites to geosynchronous equatorial orbit, OMS propellant will be a valuable commodity and saving it will be desirable even in cases where the mass savings cannot be converted into extra payload.

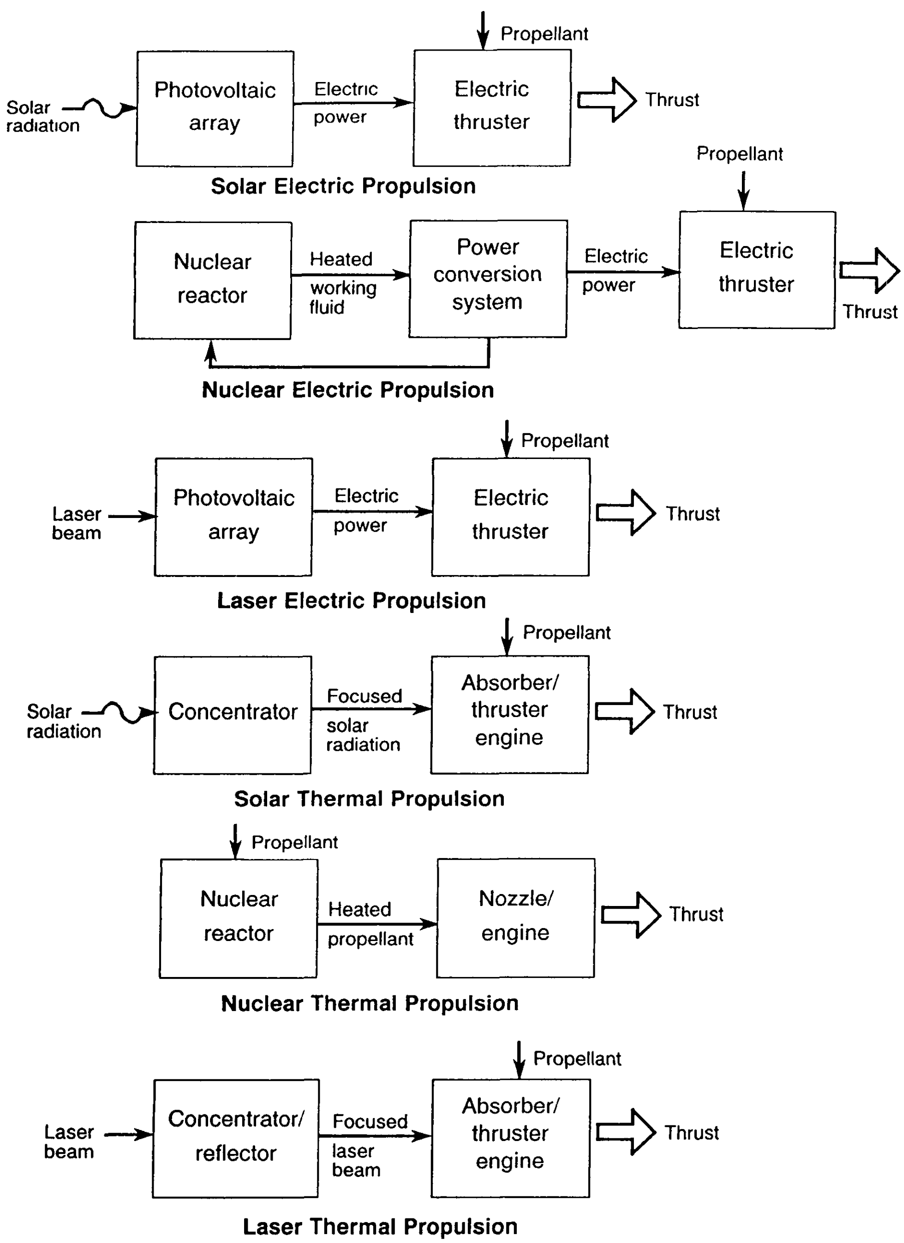


Figure 27

Electric and Thermal Propulsion Systems

Sometimes it's a little hard to tell the technologies without a scorecard. So here's a block diagram to keep things sorted out as you read the two remaining papers in this volume. In the first half of this volume, "Energy and Power," Henry Brandhorst described photovoltaic and solar dynamic power sources, Dave Buden discussed two types of nuclear power generation (radioisotope generators and nuclear reactor power plants like the SP-100), and Ed Conway presented three ways in which the Sun's energy can be used to generate a laser beam, which can then transmit its power to a distant use site. In the second half of this volume, "Transport," particularly in these last two papers, we look at ways in which these three main sources of power (solar, nuclear, and laser) can be used to drive propulsion devices

In the paper immediately following, Phil Garrison describes developments in solar electric propulsion (SEP) and nuclear electric propulsion (NEP). He discusses three types of electric propulsion devices: ion thrusters, magnetoplasmadynamic (MPD) thrusters, and arc jets. Ion thrusters can get their power from either solar or nuclear sources; MPD thrusters and arc jets use only nuclear power.

In the last paper, Jim Shoji presents two types of propulsion systems in which beamed energy is used to heat a propellant, which then provides thrust. These are solar thermal propulsion and laser thermal propulsion systems. Notice that in these cases there is no power conversion; concentrated heat from the radiation source is used directly. [A solar thermal propulsion device may be seen as analogous to a solar dynamic power

(continued)

Figure 27 (concluded)

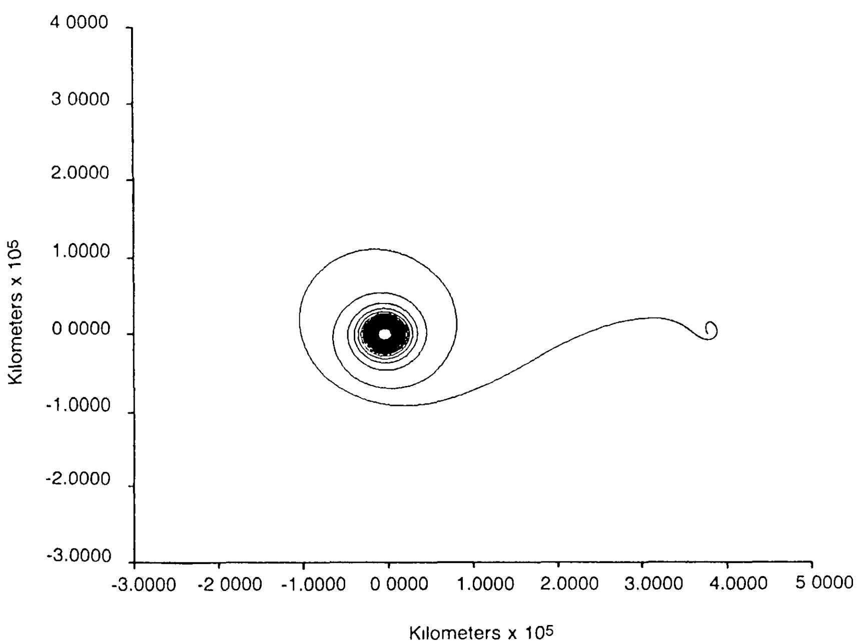
system (though in solar dynamic systems mechanical energy is finally converted to electrical power) or to the direct use of solar energy in the form of heat.] Shoji does not discuss nuclear thermal propulsion, though he is certainly aware of developments in this advanced propulsion technology. Nuclear thermal propulsion can be seen as analogous to nuclear electric propulsion, with the power conversion step omitted.

Tucked into the paper by Shoji is a short discussion by Ed Conway of laser electric propulsion (LEP). It is a form of beamed energy propulsion in which a laser beam transmits power to a photovoltaic collector on a space vehicle, where it is converted to electricity to drive the vehicle's ion engine. Thus, LEP might be seen as a variant of SEP.

Electric Propulsion

Philip W. Garrison

Electric propulsion (EP) is an attractive option for unmanned orbital transfer vehicles (OTVs). Vehicles with solar electric propulsion (SEP) and nuclear electric propulsion (NEP) could be used routinely to transport cargo between nodes in Earth, lunar, and Mars orbit. See figure 28. Electric propulsion systems are low-thrust, high-specific-impulse systems with fuel efficiencies 2 to 10 times the efficiencies of systems using chemical propellants. The payoff for this performance can be high, since a principal cost for a space transportation system is that of launching to low Earth orbit (LEO) the propellant required for operations between LEO and other nodes. See figures 29 and 30.



Distance with respect to the barycenter (that is, the center of mass of the Earth-Moon system)

Figure 28

Earth-to-Moon Trajectory for a Spacecraft Using Electric Propulsion

An electrically propelled spacecraft traveling from low Earth orbit (LEO) to lunar orbit would follow a spiral trajectory. This trajectory results from the fact that the low-thrust engines of such a vehicle work continuously. Such a smoothly changing trajectory contrasts with that of a chemical rocket, in which sharp changes in altitude or orbital plane reflect the intermittent firing of its high-thrust engines. (Compare figures 4 and 25 in this part of volume 2.)

Once the spacecraft with electric propulsion has achieved escape velocity, it coasts until it nears the Moon. Then its engines are restarted to slow the spacecraft, allowing it to be captured by the Moon's gravity and held in lunar orbit.

For missions between the Earth and the Moon, the gravitational pull of the Earth so overwhelms the low thrust provided by an electric propulsion device that trip times are much longer than those using conventional chemical rockets. For missions to the outer solar system, by contrast, the continuous acceleration provided by an electric propulsion thruster can yield shorter trip times than those afforded by chemical rockets.

Courtesy of Andrew J. Petro, Advanced Programs Office, Lyndon B. Johnson Space Center

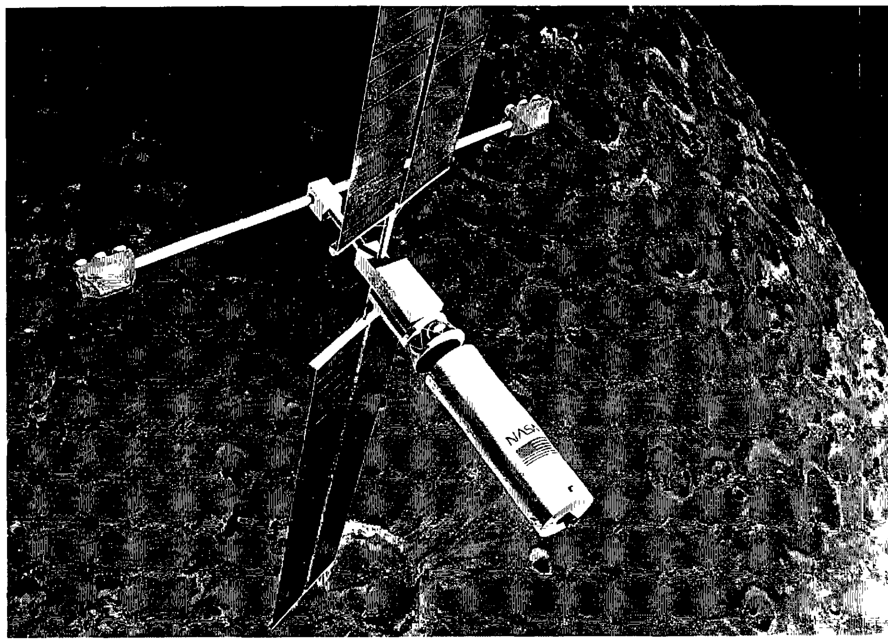


Figure 29

A Lunar Ferry Using Solar Electric Propulsion

At a power of 300 kW, in 5 years, two such lunar ferries could transfer 100 000 kg of habitat modules and power systems from low Earth orbit (LEO) to lunar orbit. The ferries and their payloads could be brought to LEO in only 12 launches of the Space Shuttle.

By contrast, transporting such a 100 000-kg payload from LEO to lunar orbit by conventional oxygen-hydrogen rockets would require about 600 000 kg of propellant, and bringing that 700 000-kg total to LEO would require 25-30 Shuttle launches

Artist. Ken Hodges

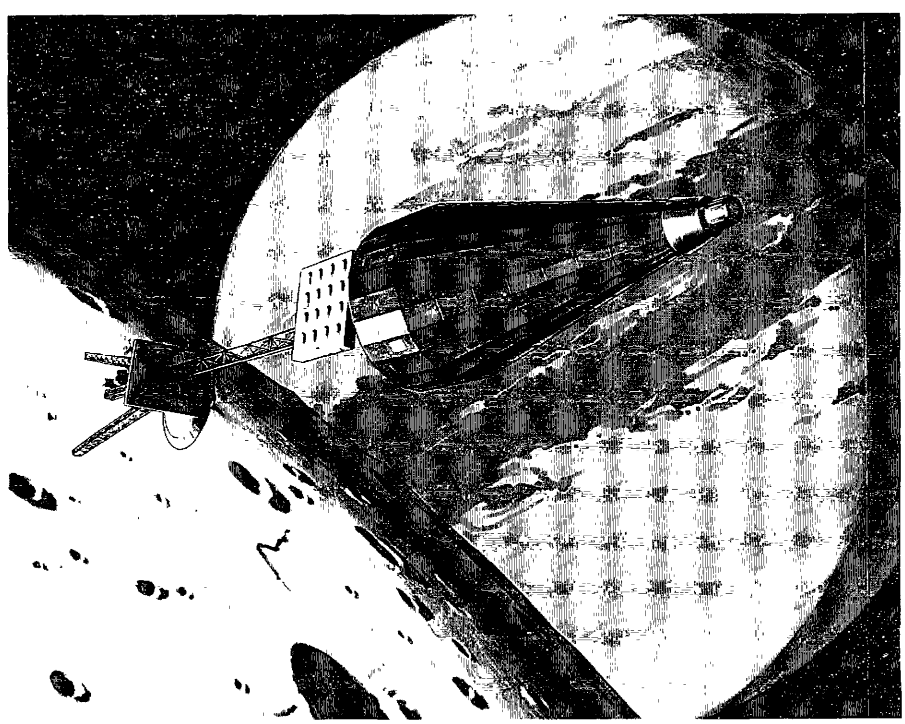


Figure 30

An Advanced Nuclear Electric Propulsion System

In this application, an advanced version of the proposed SP-100 nuclear power plant supplies electricity to an electric thruster which is being used to propel a large unmanned payload to Neptune. A 2-MW generator could place a 2000-kg payload in orbit around Neptune with a trip time of about 5 years.

In this drawing, the nuclear reactor with its radioactive material is at the tip of the conical structure. Most of the cone consists of heat radiators to remove the excess heat of the reactor. The electricity is used to expel a charged gas at very high velocity and thus propel the vehicle in the opposite direction.

Artist: Thomas Reddie

The performance of the EP orbital transfer vehicle is strongly influenced by the power-to-mass ratio of the nuclear or solar electric power system that supplies electricity to the propulsion system because the power plant must be carried along with the payload. The power requirement for cargo OTVs will be high (1-5 MW_e) for useful payloads and trip times. Advances in space power technology will reduce mass and make possible systems producing higher power. These systems, coupled with electric propulsion, will provide faster trips and permit the use of this technology for manned as well as unmanned transportation.

Candidate Systems

Electric propulsion systems of various types have been proposed for space missions. Such systems can produce much higher exhaust velocities than can conventional rockets and thus are more efficient. In a conventional rocket system, a fuel is oxidized in an exothermic reaction; the exhaust velocity is limited by the temperature of the reaction and the molecular weights of the exhaust gases. In an electric propulsion system, an electrical current is used to ionize the propellant and to accelerate the ions to a much higher velocity. In the simple case of an ion thruster, ions are generated, accelerated across a voltage potential, and emitted through a nozzle. Because of the high velocity of the ions, such a device has a very high specific impulse (a measure of engine performance or efficiency; see p. 90).

With existing power systems, electric propulsion devices can produce only low thrust. However, emerging high-power systems will enable both ion engines that can produce higher thrust and other types of electric engines. Magnetoplasmadynamic (MPD) thrusters use power systems operating at 10-20 kV and at 12 000 amperes. The large current creates a magnetic field that can accelerate ions to 15-80 km/sec. An alternative system, called an arc jet, uses a high voltage arc, drawn between electrodes, to heat the propellant (hydrogen) to a high temperature.

Figure 31

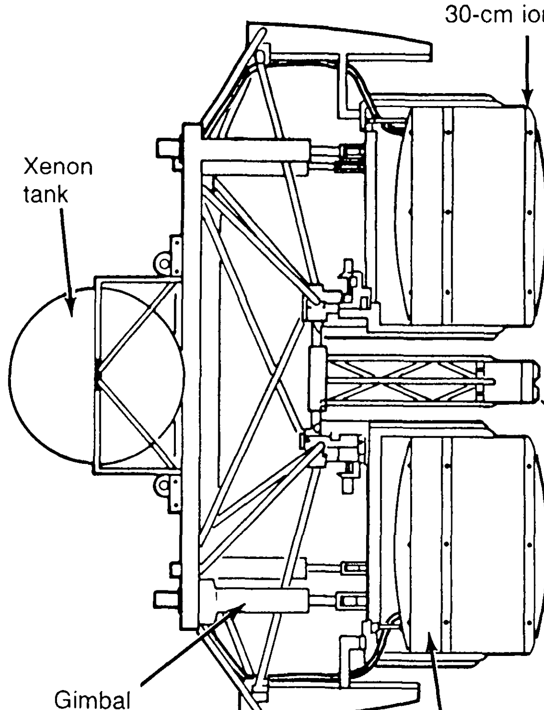
Ion Thruster

Because of its potential for providing very high exhaust velocity (10^5 meters per second) and high efficiency, ion propulsion is well suited to meet the high energy needs of planetary missions. Research is being directed toward improving the life and reliablity of the mercury ion thruster and toward developing ion thrusters that use inert gases.

Lewis Research Center (LeRC) successfully operated a 30-cm xenon thruster at approximately 20 kW, more than five times the thrust per unit area of its predecessor mercury thruster. LeRC is investigating the performance and lifetime of the 30-cm xenon thruster and designing and testing a 50-cm ion thruster with the potential to use 60 kW of power.

*The Jet Propulsion Laboratory (JPL) has designed and begun testing a two-engine xenon ion propulsion module. At a power input of 10 kW for the module, the maximum thrust and exhaust velocity are projected to be 0.4 N and 3.5×10^4 m/sec, for a total module efficiency of 67 percent.**

The principal focus of the U.S. electric propulsion technology program has been the J-series 30-cm mercury ion thruster. This technology is reasonably mature but not yet flight qualified. Mercury may not be an acceptable propellant for heavy OTV traffic operating from Earth orbit. Ion thrusters are currently being developed for argon and xenon (see fig. 31). Specific impulses between 2 000 and 10 000 seconds are possible, but a value less than 3 000 seconds is typically optimum for these missions.



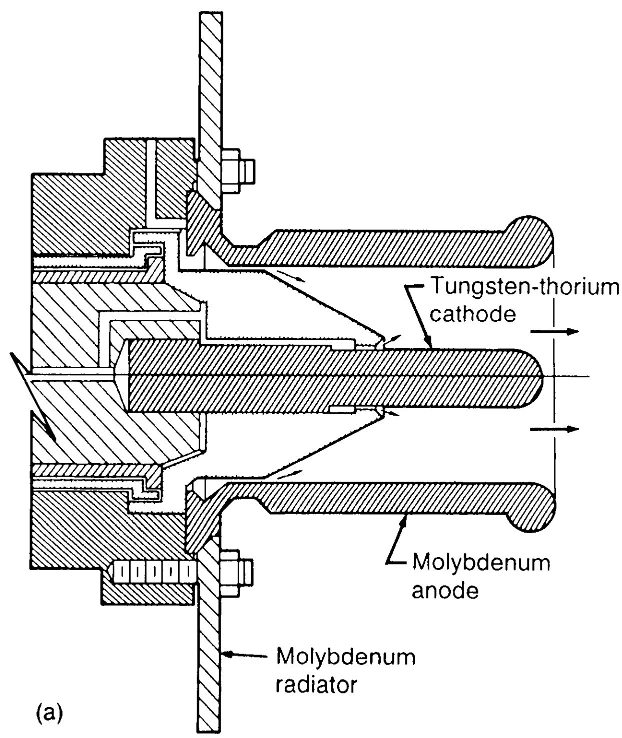
**Because jet power equals its kinetic energy ($1/2\ mv^2$) over time (t) and mv/t is an expression of force, the output power of a jet engine is expressed as 1/2 its thrust (F) times its exhaust velocity (v) and*

$$\text{Efficiency } (\eta) = \frac{\text{output power}}{\text{input power}} =$$

$$\frac{1/2 \text{ thrust} \times \text{exhaust velocity}}{\text{input power}} =$$

$$\frac{0.4 \text{ N } (3.5 \times 10^4 \text{ m/sec})}{2 \times 10 \text{ kW}} = 0.7$$

Magnetoplasmadynamic thruster technology is also being developed in the United States and elsewhere, but it is significantly less mature than mercury ion or arc jet technology. MPD thrusters (see fig. 32) can operate with a wide range of propellants providing specific impulses of approximately 2 000 sec using argon and up to 10 000 sec using hydrogen. MPD thrusters operate in both pulsed and steady-state modes. A steady-state MPD thruster is a high-power device (approximately 1 MW_e) and is an attractive option for EP OTV applications.



(a)

Figure 32

Magnetoplasmadynamic Thruster

Studies show that multimegawatt nuclear-powered magnetoplasmadynamic (MPD) propulsion is well suited to orbit transfer and spacecraft maneuvering. MPD research, sponsored by NASA, the Air Force Office of Scientific Research (AFOSR), and the Air Force Rocket Propulsion Laboratory (AFRPL), is being conducted at JPL, Princeton University, and MIT.

In an MPD device, the current flowing from the cathode to the anode sets up a ring-shaped magnetic field, B_Θ.

This magnetic field pushes against the plasma in the arc. As propellant flows through the arc plasma, it is ionized and blown away by the magnetic field

[In this explanation one can see how ion thrusters, MPD thrusters, and arc jets are related. Furthermore, one can perceive similarities in operating principles between the MPD device and an electromagnetic launcher (discussed in Snow's paper) and an electrodynamic tether (discussed in the immediately preceding paper by Cutler) and, for that matter, an ordinary electric motor In all four of these cases, a force is created by the interaction of an electrical current and a magnetic field.]

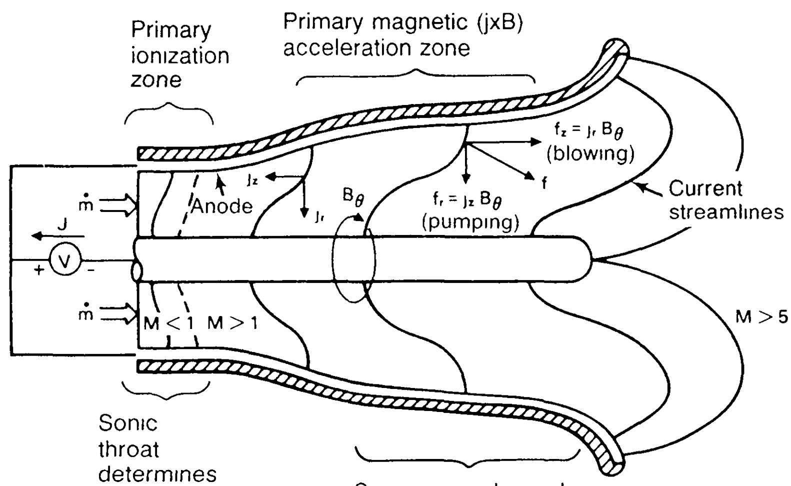
The objective of this work is to develop an improved understanding of the physics of the magnetic field set up by the arc and the acceleration process produced by that field. This understanding, it is hoped, will lead to thruster lifetimes of thousands of hours and to efficiencies above 50 percent. Measurements and analyses

(continued)

Figure 32 (concluded)

have shown that the cathode can efficiently operate at temperatures where metal evaporation from it does not limit thruster life. Experiments are being conducted to measure cathode life in the subscale 100-kW engine shown in this figure.

Diagram b taken from Edmund P. Coomes et al., 1986, Pegasus: A Multi-Megawatt Nuclear Electric Propulsion System, in vol. 2 of Manned Mars Missions Working Group Papers, pp. 769-786, NASA Report M002 (Huntsville, AL: Marshall Space Flight Center).



(b)

Extensive work was done on arc jet and resistojet technology in the 1960s, but this technology has received little attention in recent years. The arc jet (see fig. 33) is also a high-power device and provides a specific impulse between 900 and 2000 sec. The arc jet, like the MPD thruster, can operate with a wide variety of propellants.

Research conducted at the Jet Propulsion Laboratory since 1984 (see Aston 1986, Garrison 1986) has demonstrated the successful operation of (1) a 30-cm ion thruster at 5 kW and 3600 seconds with xenon propellant, (2) a steady-state MPD thruster at 60 kW with argon propellant, and (3) an arc jet for 573 hours at 30 kW with ammonia propellant. NASA's Lewis Research Center has recently initiated programs to develop the technology for 50-cm, 30-kW xenon ion thrusters and low-power arc jets. The Air Force is funding research in MPD thrusters at Princeton University and MIT and in high-power arc jets at Rocket Research Corporation.

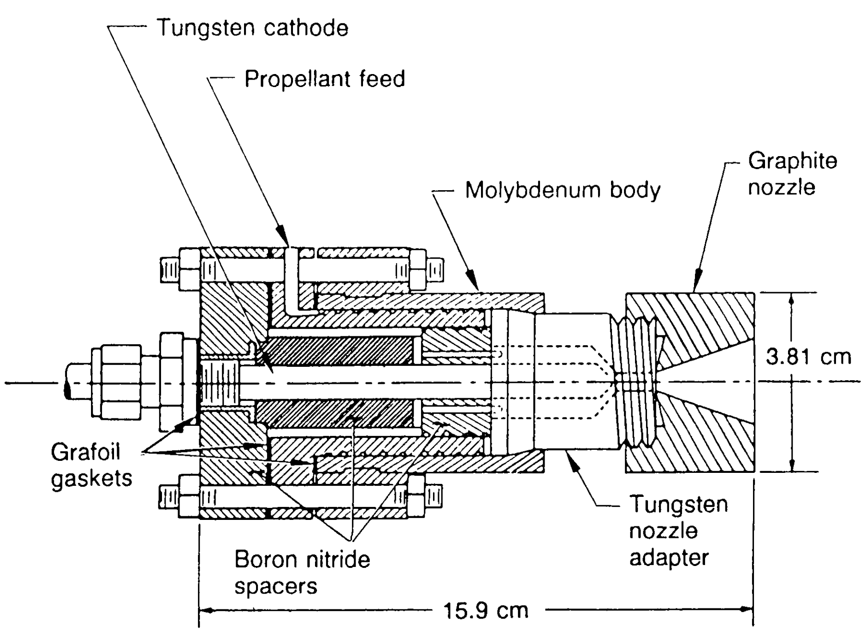


Figure 33

Arc Jet

A high-power arc jet with exhaust velocities between 8 x 10^3 and 2 x 10^4 meters per second is an attractive option for propelling an orbital transfer vehicle. Experimental and analytical work, sponsored by the Air Force Rocket Propulsion Laboratory (AFRPL) and conducted at JPL and at Rocket Research, is addressing the technology of this class of engine.

During 1985, two new arc jet test facilities were built. Tests at JPL of a 30-kW engine have provided new information about the effects of arc jet nozzle contour on engine performance. Tests at Rocket Research of an arc jet using ammonia as its propellant and operating at power levels in the 10-50 kW range have mapped the stability and measured the performance of such an engine.

Technology Needs

Because of the difficulty of developing larger ion thrusters, large numbers of ion thrusters are required for a multimegawatt OTV. Steady-state MPD thrusters and arc jets are likely to be better suited to the cargo OTV application. Of the two, the arc jet is the more mature technology.

The funding for each of the above EP technologies is nearly subcritical because there is no established mission requirement for the technology. Increased funding will be necessary to make this technology available for the scenarios under consideration.

Impact of Scenarios Utilizing Nonterrestrial Materials

Nonterrestrial material utilization has two potential impacts on EP technology needs. If a demand for large quantities of lunar materials is established, electric propulsion is a highly competitive option for transporting both the bulk materials needed to construct the bases and factories for such an operation and the raw materials and products output by it. Electrically propelled OTVs, such as the lunar ferry described in figure 29, can beneficially supplant chemically propelled vehicles when cargo traffic to and from the Moon reaches some level, perhaps 100 metric tons (100 000 kg) per year. The second impact concerns the ability of the transportation system to rely on nonterrestrial resources for resupply of consumables. All other aspects being equal, a system that can be resupplied from local resources is clearly preferred.

However, the most readily available lunar propellant, oxygen, is not well suited to EP operations. Significant technology advances are required to operate any of the EP devices with oxygen, the principal technology barriers being the development of techniques to prevent the rapid oxidation of high-temperature thruster components. On the other hand, if hydrogen could be obtained from lunar (or asteroidal) sources, it would significantly enhance the performance of the EP OTV as well as benefit the oxygen-hydrogen chemical propulsion vehicles needed for high-thrust surface-to-orbit operations.

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Beamed Energy Propulsion

James M. Shoji

Beamed energy concepts offer an alternative for an advanced propulsion system. The use of a remote power source reduces the weight of the propulsion system in flight and this, combined with the high performance, provides significant payload gains. Within the context of this study's baseline scenario, two beamed energy propulsion concepts are potentially attractive: solar thermal propulsion and laser thermal propulsion. The conceived beamed energy propulsion devices generally provide low thrust (tens of pounds to hundreds of pounds); therefore, they are typically suggested for cargo transportation. For the baseline scenario, these propulsion systems can provide propulsion between the following nodes (see fig. 34):

a. 2-3 (low Earth orbit to geosynchronous Earth orbit)
b. 2-4 (low Earth orbit to low lunar orbit)
c. 4-7 (low lunar orbit to low Mars orbit)—only solar thermal
d. 5-4 (lunar surface to low lunar orbit)—only laser thermal

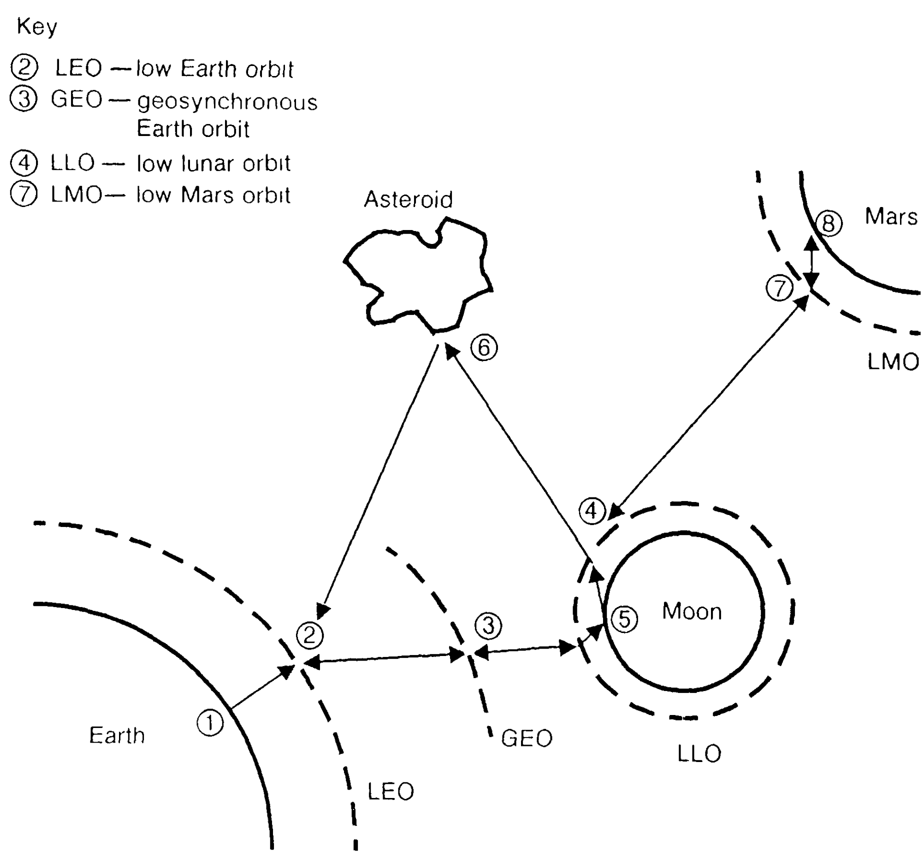
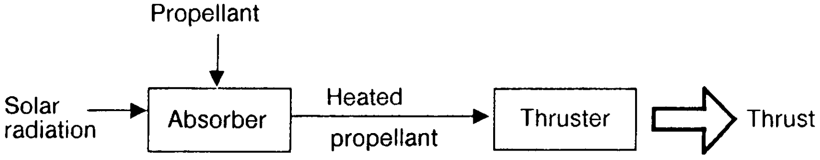


Figure 34

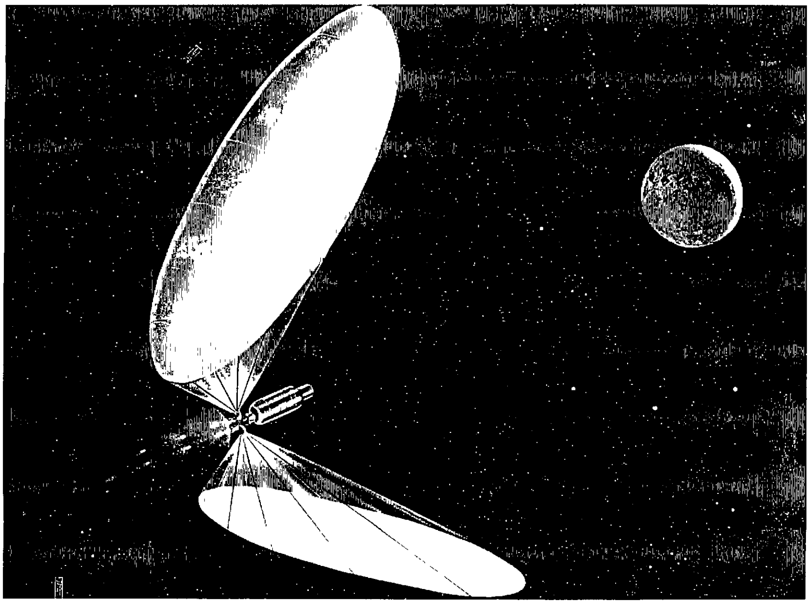
Transportation Nodes

Solar Thermal Propulsion

Solar thermal propulsion makes use of an available power source, the Sun, and therefore does not require development of the power source. Rather than carrying a heavy generator with the spacecraft, a solar thermal rocket has to carry only the means of capturing solar energy, such as concentrators and mirrors. Instead of converting that solar energy to electrical power, as photovoltaic systems do, a solar thermal propulsion system uses the solar energy directly—as heat. As shown in figure 35, the solar radiation is collected and focused to heat a propellant. This solar thermal propulsion configuration is discussed in detail by Etheridge (1979). The heated propellant is fed through a conventional converging-diverging nozzle to produce thrust. For the baseline scenario, hydrogen from the Earth is used as the propellant. The engine thrust is directly related to the surface area of the solar collector.



(a)



(b)

Figure 35

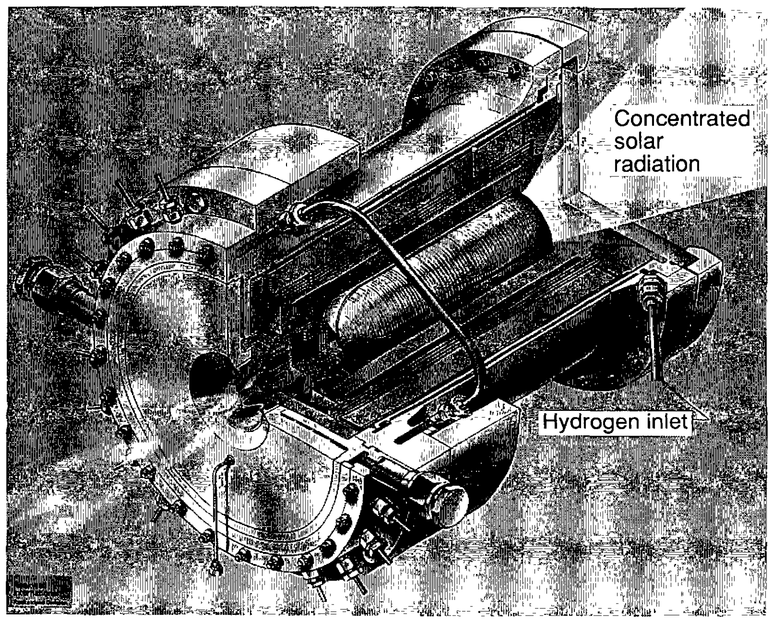
Solar Thermal Propulsion
a. Concept

Solar thermal propulsion is a beamed energy system in which the source of power is a natural one—the Sun. The Sun's rays are concentrated and used to heat a propellant. The expanding propellant is then directed through a nozzle to produce thrust The Air Force Rocket Propulsion Laboratory (AFRPL), with support from Rocketdyne, L'Garde, and Spectra Research, has been working in this area. The objective of this program is to produce lightweight, efficient concentrators and simple, reliable thrusters for a solar rocket.

b. Solar Thermal Rocket Including Collectors

The performance of a solar rocket depends on its having lightweight collectors that can concentrate the solar heat. An inflatable reflector, 3 meters in diameter, has been built. It has a surface accuracy of 2.8 milliradians (root mean square).

(continued)



(c)

Figure 35 (concluded)

c. Solar Thermal Thruster (Rocketdyne)

The Rocketdyne heat exchanger thruster shown is currently being tested. Using hydrogen propellant at a temperature of 2700 K, it has produced a thrust of 3.7 newtons and an exhaust velocity of 7900 meters per second.

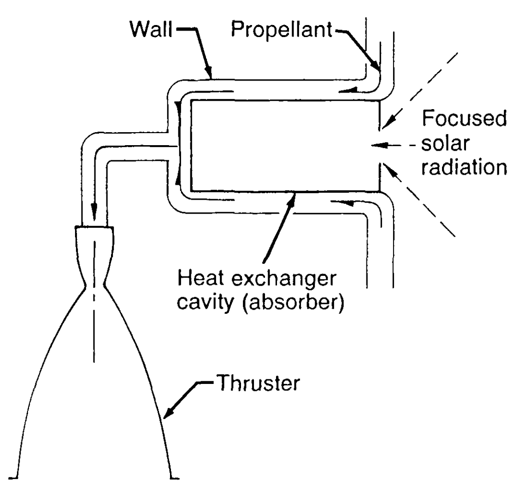


Figure 36

Windowless Heat Exchanger Cavity

There are two basic solar thermal propulsion concepts. These involve indirect and direct solar radiation absorption and differ primarily in the method of heating the propellant (Shoji 1983).

Indirect solar radiation absorption involves flowing a propellant through passages in a wall that is heated. The windowless heat exchanger cavity concept (fig. 36) is a state-of-the-art design taking this radiation absorption approach.

The rotating bed concept (fig. 37) is one of the preferred concepts for direct solar radiation absorption. Of the solar thermal propulsion concepts, it offers the highest specific impulse by using a retained seed (tantalum carbide or hafnium carbide) approach. The propellant flows through the porous walls of a rotating cylinder, picking up heat from the seeds, which are retained on the walls by centrifugal force. The carbides are stable at high temperatures and have excellent heat transfer properties.

A comparison of the performance potential of the indirect and direct heating concepts for one collector with a diameter of 100 feet (30.5 meters) using hydrogen as propellant is presented in figure 38. Because of limitations in wall material temperature (less than 5000°R or 2800 K), the indirect absorption concepts are limited to delivered specific impulses approaching 900 sec. The direct absorption concepts enable higher propellant temperatures and therefore higher specific impulses (approaching 1200 sec). Even the lower specific impulse represents a significant increase over that of conventional chemical propulsion, an increase that can provide substantial payload gains (45 percent for a LEO-to-GEO mission) at the expense of increased trip time (14 days compared to 10 hours).

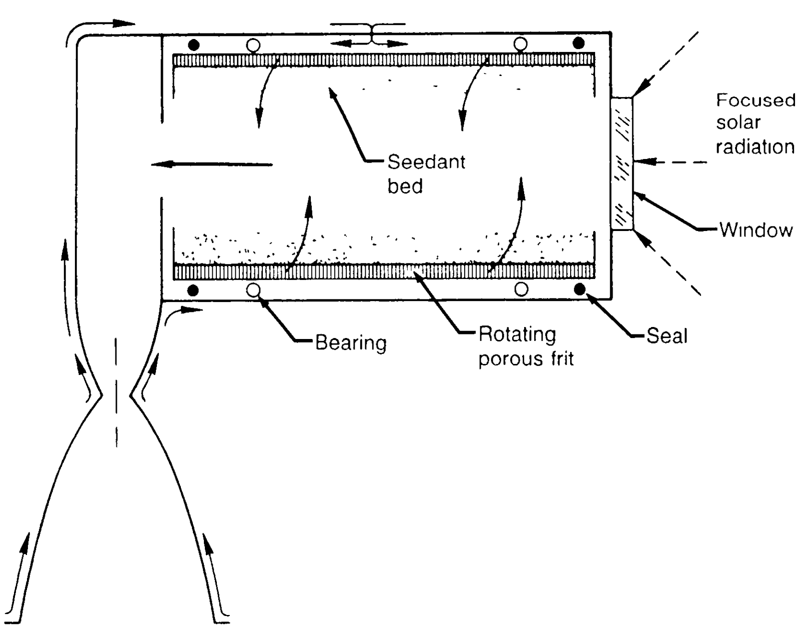


Figure 37

Rotating Bed Concept

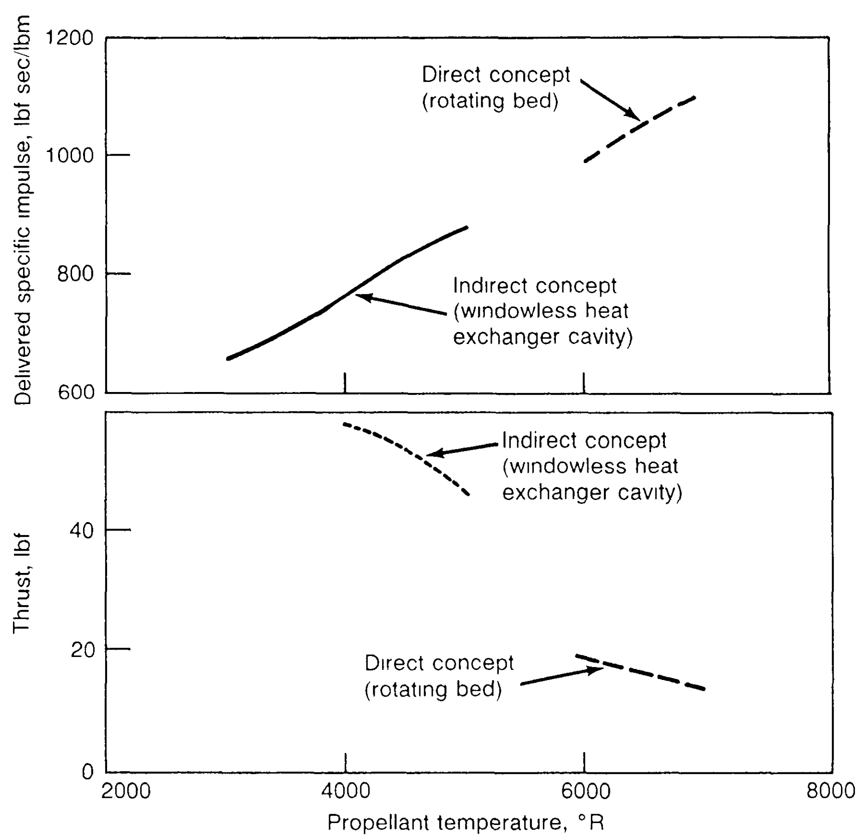


Figure 38

Comparison of Performance of the Indirect and Direct Absorption Concepts for a Solar Thermal Rocket Having One Collector 100 Feet in Diameter

Note = 100-to-1
ε = nozzle area ratio (that is, nozzle exit area - throat area)

The state of the art of solar thermal propulsion is that the absorber/thruster of the indirect solar radiation absorption approach is in the proof-of-principle stage. Small-scale hardware has been designed and fabricated for the Air Force Rocket Propulsion Laboratory (AFRPL) for ground test evaluation (see fig. 35). In order to provide solar thermal propulsion for the baseline mission scenario, a number of technology advances must be made, including the following:

1. Propulsion system
   a. Indirect solar radiation absorption concept
      - Further high-temperature material fabrication and process technology
      - Concept design and development
   b. Direct solar radiation absorption concept
      - Subcomponent and component technology
      - Concept design and development
   c. Engine system
      - Absorber concept selection
      - Complete engine system design and development
2. Collector/concentrator—component technology associated with large inflated collector
   a. Structural design
   b. High concentration ratios
   c. Deployment approach and design
   d. Collector surface accuracy
3. Vehicle
   a. Collector/concentrator integration
   b. Sun-tracking system
   c. Long-term storage of liquid hydrogen for LLO-to-LMO missions

Details of the technology needs are outlined by Caveny (1984).

An acceleration in the technology schedule and an increase in funding level would be required to provide solar thermal propulsion for the LEO-to-GEO leg for the year 2000 and to support the lunar and Mars missions in the baseline scenario.

Laser Thermal Propulsion

Laser thermal propulsion uses a remotely located power source for propulsion in low Earth orbit (LEO), between LEO and geosynchronous Earth orbit (GEO), or on the Moon. A remotely located laser transmits energy to the transportation system, where it is converted to heat in a propellant; then the heated propellant is discharged through a nozzle to produce thrust (see fig. 39).

Laser thermal propulsion concepts can be grouped into continuous wave (CW) and repetitive pulsed (RP) concepts. The CW concepts include (1) indirect heating (heat exchanger), (2) molecular or particulate seedant, and (3) inverse Bremstrahlung. Details of these concepts are described by Caveny (1984). The inverse Bremstrahlung concept (fig. 40) enables the propellant to be taken to the highest temperatures (exceeding 10 000°R or 5500 K) and to be of the lowest molecular weight (approaching 1.0) through the formation of a high-temperature plasma and therefore results in the highest specific impulses (1000 to 2000 sec) of all the laser thermal propulsion concepts.

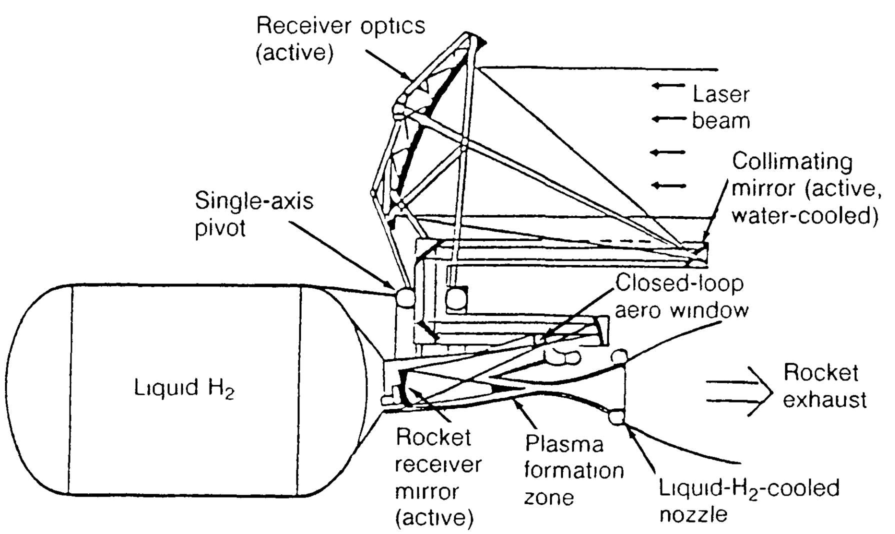


Figure 39

Typical Laser Thermal Rocket Concept

The repetitive pulsed concept (fig. 41) uses a pulsed laser and a laser-supported detonation wave within the propellant to provide a rapidly pulsed, high-performance system.

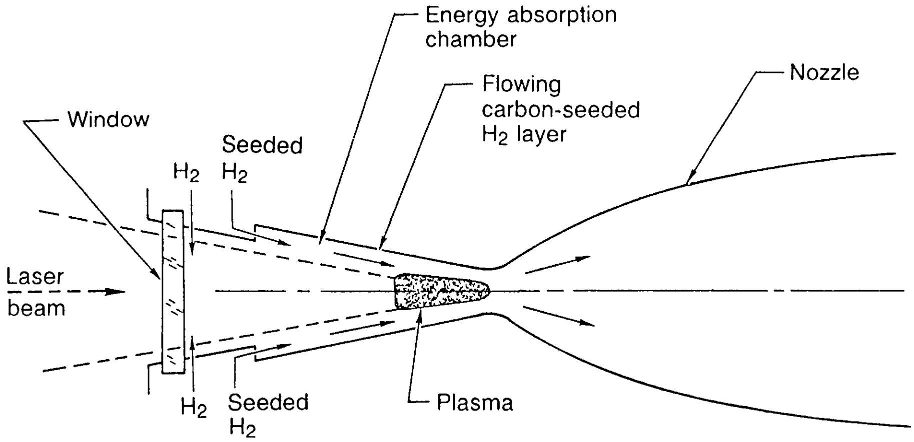


Figure 40

Inverse Bremstrahlung Concept

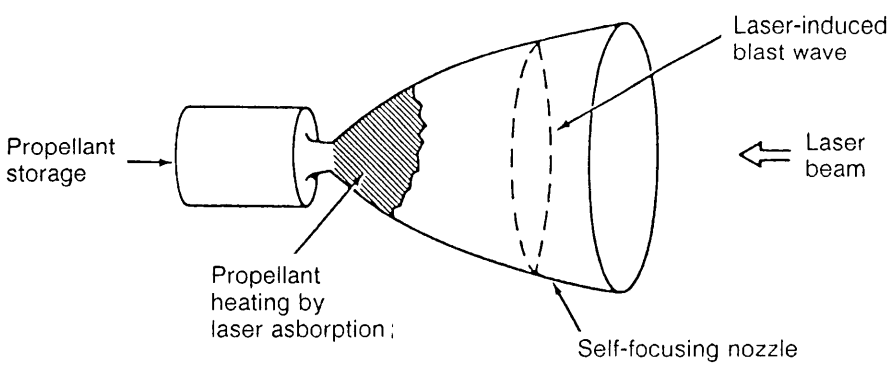


Figure 41

Repetitive Pulsed Laser Propulsion Concept

The state of the art of laser thermal propulsion has been constrained by the available funding and is dependent on the development of a laser system capable of transmitting high levels (multimegawatts) of power. Analytical and experimental studies have been conducted to investigate the physics involved in plasma initiation and formation for the inverse Bremstrahlung approach. Also, initial small-scale RP thruster experiments have been conducted (Caveny 1984). NASA's plans include an experimental CW laser thruster. The technology advances required to provide laser thermal propulsion include the following:

1. Thruster
   a. Thruster cooling approach
   The high plasma temperatures (greater than 20 000°R or 11 000 K) and the high specific impulse involved make satisfactory cooling difficult. A combination of regenerative and/or transpiration cooling with high-temperature wall materials may be required.
   b. Window design and cooling
      - High transmittance
      - Low absorptivity
      - High strength at high temperatures
2. Collector/concentrator
   a. Surface accuracy
   Although laser thermal propulsion concentrators will be smaller than those for solar thermal propulsion, the requirement for surface accuracy may be more stringent because of the short wavelengths involved.

   Other concentrator technologies are similar to those of the solar concentrator:

   b. High concentration ratios
   c. Structural design
   d. Deployment approach and design
3. Vehicle
   a. Collector/concentrator integration
   b. Long-term cryogenic propellant storage

Further specific technology requirements for both CW and RP laser thermal propulsion concepts are presented by Caveny (1984). In addition, an accurate laser-vehicle tracking system is essential.

For laser thermal propulsion to become a viable approach, the current NASA plan would need to be accelerated, funding increased, and a space-based laser system developed.

Laser Electric Propulsion

Edmund J. Conway

In laser electric propulsion (LEP), power is beamed to a photovoltaic collector on a space vehicle, where it is converted to electricity for an ion engine (Holloway and Garrett 1981). The central power station can remain fixed, generating the laser beam and aiming it at the spacecraft receiver. Because of the high power in the laser beam, the spacecraft photovoltaic converter can be reduced in area (and thus mass), with respect to the array of a solar electric propulsion (SEP) system, by a factor of 10^2 to 10^4. As a laser photovoltaic array can be 50-percent efficient while solar photovoltaic array efficiency will not exceed 20 percent, the radiator area can also be significantly reduced. The reduced size of the converter and radiator implies a much reduced drag (compared to SEP) in low orbit. Moreover, ion engines are well developed, having high specific impulse, low thrust, and long life.

Use of Nonterrestrial Resources for Beamed Energy Propulsion

Beamed energy propulsion alternatives utilizing propellants produced from nonterrestrial resources are summarized in table 11. In general, for both solar and laser thermal propulsion concepts, the availability of oxygen as propellant through lunar soil processing is not expected to be attractive because of the difficulty of achieving the required high-temperature oxygen-resistant materials for the thruster, the poor cooling capacity of oxygen, and the low specific impulse potential of oxygen. Even if these problems were solved, a performance and cost tradeoff analysis must be performed to quantify any gains. The oxygen would be available for missions originating from or returning to the lunar surface.

The availability of water from Earth-crossing asteroids (or from the moons of Mars, Phobos and Deimos) transported to LEO would enable water electrolysis to produce hydrogen and oxygen.

TABLE 11. *Beamed Energy Propulsion Alternatives Utilizing Propellants Produced From Nonterrestrial Resources*

Nodes [see fig. 34]	Propellant	Solar and laser thermal propulsion alternative	Technology required	Mission impact
• 2 ⟷ 4 (LEO to LLO & return) • 4 ⟷ 6 (LLO to asteroid & return) • 6 ⟷ 2 (asteroid to LEO & return)	• Lunar O_2	O_2 based	• High-temperature oxygen-resistant materials for thruster (design feasibility) • O_2 laser radiation absorption	• Requires performance (payload) & cost tradeoff between available low I_{sp} O_2 & high I_{sp} H_2 which must be transported from Earth
	• Lunar H_2 • Asteroid H_2O	H_2 based (H_2 production in LEO)	• Same as using H_2 from Earth • Cryogenic fluid transfer • Long-term H_2 storage	• Potential cost & performance (payload) gains through available H_2
5 ⟷ 4 (Moon to LLO & return)	Lunar O_2	O_2 based	Same as for 2 ⟷ 4	Same as for 2 ⟷ 4
4 ⟷ 7 (LLO to LMO & return)	Lunar O_2	O_2 based	Same as for 2 ⟷ 4	Same as for 2 ⟷ 4
2 ⟷ 7 (LEO to LMO & return)	• Lunar O_2 • Lunar H_2 • Asteroid H_2O	• O_2 based • H_2 based (H_2 production in LEO)	• Same as for 2 ⟷ 4 • Same as using H_2 from Earth • Cryogenic fluid transfer • Long-term H_2 storage	• Same as for 2 ⟷ 4 • Potential cost & performance (payload) gains through available H_2

The hydrogen produced could be used in both the solar and laser thermal propulsion concepts. Another possible nonterrestrial source of hydrogen is lunar soil. Hydrogen implanted by the solar wind is present in abundances of about 40 ppm in the bulk soil and up to 300 ppm in fine-grained fractions. Extraction of this hydrogen is being studied to determine whether it is economically attractive compared to importing hydrogen from Earth. An abundance of 300 ppm hydrogen by weight is equivalent to 2700 ppm, or 0.27 percent, water. This amount of hydrogen has been found in the fine-grained (less than 20 micrometers in diameter) fractions of some mature lunar soils. The technology required to use this hydrogen is the same as that to use hydrogen brought from the Earth in the baseline scenario. Additional technology needed for the alternative scenario includes long-term cryogenic propellant storage. Again, a performance and cost tradeoff analysis is required to evaluate the gains achieved through the availability of hydrogen.

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Addendum: Participants

The managers of the 1984 summer study were

David S. McKay, Summer Study Co-Director and Workshop Manager
Lyndon B. Johnson Space Center

Stewart Nozette, Summer Study Co-Director
California Space Institute

James Arnold, Director
of the California Space Institute

Stanley R Sadin, Summer Study Sponsor
for the Office of Aeronautics and Space Technology
NASA Headquarters

Those who participated in the 10-week summer study as faculty fellows were the following:

James D. Burke	Jet Propulsion Laboratory
James L. Carter	University of Texas, Dallas
David R. Criswell	California Space Institute
Carolyn Dry	Virginia Polytechnic Institute
Rocco Fazzolare	University of Arizona
Tom W. Fogwell	Texas A & M University
Michael J. Gaffey	Rensselaer Polytechnic Institute
Nathan C. Goldman	University of Texas, Austin
Philip R Harris	California Space Institute
Karl R. Johansson	North Texas State University
Elbert A. King	University of Houston, University Park
Jesa Kreiner	California State University, Fullerton
John S. Lewis	University of Arizona
Robert H. Lewis	Washington University, St. Louis
William Lewis	Clemson University
James Grier Miller	University of California, Los Angeles
Sankar Sastri	New York City Technical College
Michele Small	California Space Institute

Participants in the 1-week workshops included the following:

Constance F. Acton	Bechtel Power Corp.
William N. Agosto	Lunar Industries, Inc.
A. Edward Bence	Exxon Mineral Company
Edward Bock	General Dynamics
David F. Bowersox	Los Alamos National Laboratory
Henry W. Brandhorst, Jr.	NASA Lewis Research Center
David Buden	NASA Headquarters
Edmund J. Conway	NASA Langley Research Center
Gene Corley	Portland Cement Association
Hubert Davis	Eagle Engineering
Michael B. Duke	NASA Johnson Space Center
Charles H. Eldred	NASA Langley Research Center
Greg Fawkes	Pegasus Software
Ben R. Finney	University of Hawaii
Philip W. Garrison	Jet Propulsion Laboratory
Richard E. Gertsch	Colorado School of Mines
Mark Giampapa	University of Arizona
Charles E. Glass	University of Arizona
Charles L. Gould	Rockwell International
Joel S. Greenberg	Princeton Synergetics, Inc.
Larry A. Haskin	Washington University, St. Louis
Abe Hertzberg	University of Washington
Walter J. Hickel	Yukon Pacific
Christian W. Knudsen	Carbotek, Inc.
Eugene Konecci	University of Texas, Austin
George Kozmetsky	University of Texas, Austin
John Landis	Stone & Webster Engineering Corp.
T. D. Lin	Construction Technology Laboratories
John M. Logsdon	George Washington University
Ronald Maehl	RCA Astro-Electronics
Thomas T. Meek	Los Alamos National Laboratory
Wendell W. Mendell	NASA Johnson Space Center
George Mueller	Consultant
Kathleen J. Murphy	Consultant
Barney B. Roberts	NASA Johnson Space Center
Sanders D. Rosenberg	Aerojet TechSystems Company
Robert Salkeld	Consultant
Donald R. Saxton	NASA Marshall Space Flight Center
James M. Shoji	Rockwell International
Michael C. Simon	General Dynamics
William R. Snow	Electromagnetic Launch Research, Inc.
Robert L. Staehle	Jet Propulsion Laboratory
Frank W. Stephenson, Jr.	NASA Headquarters
Wolfgang Steurer	Jet Propulsion Laboratory
Richard Tangum	University of Texas, San Antonio
Mead Treadwell	Yukon Pacific
Terry Triffet	University of Arizona
J. Peter Vajk	Consultant
Jesco von Puttkamer	NASA Headquarters
Scott Webster	Orbital Systems Company
Gordon R. Woodcock	Boeing Aerospace Company

The following people participated in the summer study as guest speakers and consultants:

Edwin E. "Buzz" Aldrin	Research & Engineering Consultants
Rudi Beichel	Aerojet TechSystems Company
David G. Brin	California Space Institute
Joseph A. Carroll	California Space Institute
Manuel I. Cruz	Jet Propulsion Laboratory
Andrew H. Cutler	California Space Institute
Christopher England	Engineering Research Group
Edward A. Gabris	NASA Headquarters
Peter Hammerling	LaJolla Institute
Eleanor F. Helin	Jet Propulsion Laboratory
Nicholas Johnson	Teledyne Brown Engineering
Joseph P. Kerwin	NASA Johnson Space Center
Joseph P. Loftus	NASA Johnson Space Center
Budd Love	Consultant
John J. Martin	NASA Headquarters
John Meson	Defense Advanced Research Projects Agency
Tom Meyer	Boulder Center for Science and Policy
John C. Niehoff	Science Applications International
Tadahiko Okumura	Shimizu Construction Company
Thomas O. Paine	Consultant
William L. Quaide	NASA Headquarters
Namika Raby	University of California, San Diego
Donald G. Rea	Jet Propulsion Laboratory
Gene Roddenberry	Writer
Harrison H. "Jack" Schmitt	Consultant
Richard Schubert	NASA Headquarters
Elie Shneour	Biosystems Associates, Ltd.
Martin Spence	Shimizu Construction Company
James B. Stephens	Jet Propulsion Laboratory
Pat Sumi	San Diego Unified School District
Robert Waldron	Rockwell International
Simon P Worden	Department of Defense
William Wright	Defense Advanced Research Projects Agency

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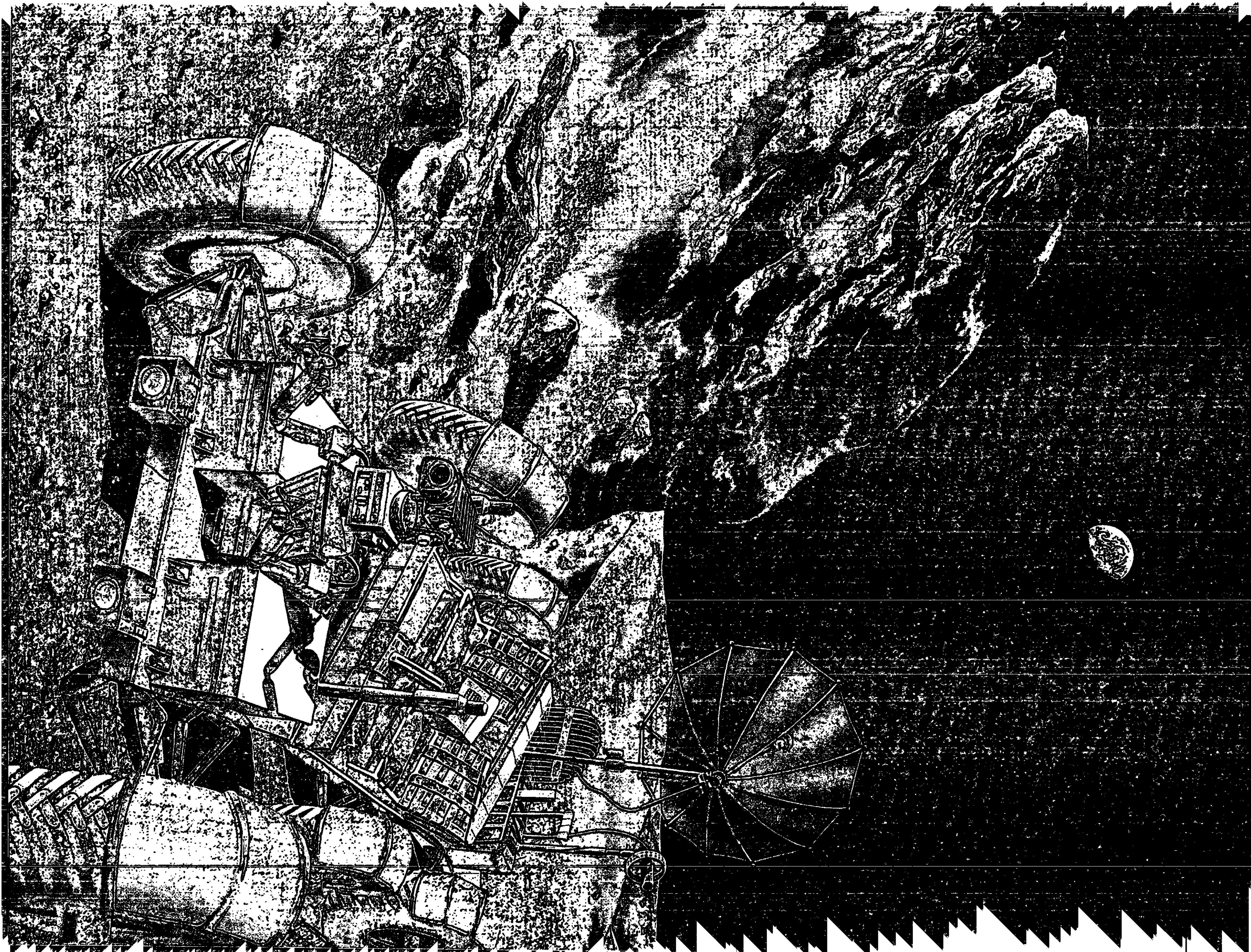

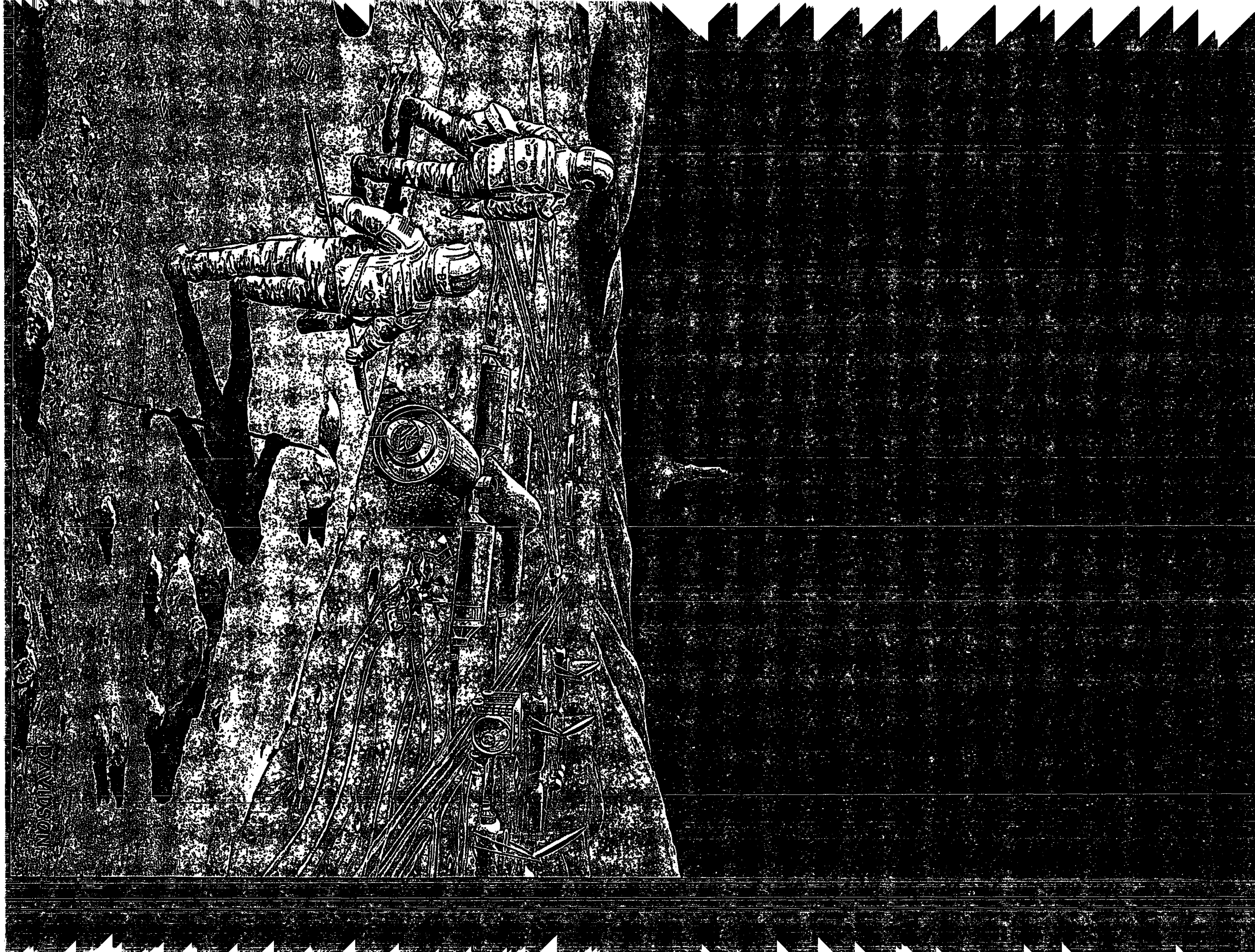
DAVIDSON

Frontispiece

Advanced Lunar Base

In this panorama of an advanced lunar base, the main habitation modules in the background to the right are shown being covered by lunar soil for radiation protection. The modules on the far right are reactors in which lunar soil is being processed to provide oxygen. Each reactor is heated by a solar mirror. The vehicle near them is collecting liquid oxygen from the reactor complex and will transport it to the launch pad in the background, where a tanker is just lifting off. The mining pits are shown just behind the foreground figure on the left. The geologists in the foreground are looking for richer ores to mine.

Artist: Dennis Davidson

Space Resources

Materials

Editors

Mary Fae McKay, David S. McKay, and Michael B. Duke

Lyndon B. Johnson Space Center
Houston, Texas

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Preface

Space resources must be used to support life on the Moon and exploration of Mars. Just as the pioneers applied the tools they brought with them to resources they found along the way rather than trying to haul all their needs over a long supply line, so too must space travelers apply their high technology tools to local resources.

The pioneers refilled their water barrels at each river they forded; moonbase inhabitants may use chemical reactors to combine hydrogen brought from Earth with oxygen found in lunar soil to make their water. The pioneers sought temporary shelter under trees or in the lee of a cliff and built sod houses as their first homes on the new land; settlers of the Moon may seek out lava tubes for their shelter or cover space station modules with lunar regolith for radiation protection. The pioneers moved further west from their first settlements, using wagons they had built from local wood and pack animals they had raised; space explorers may use propellant made at a lunar base to take them on to Mars.

The concept for this report was developed at a NASA-sponsored summer study in 1984. The program was held on the Scripps campus of the University of California at San Diego (UCSD), under the auspices of the American Society for Engineering Education (ASEE). It was jointly managed by the California Space Institute and the Lyndon B. Johnson Space Center, under the direction of the Office of Aeronautics and Space Technology (OAST) at NASA Headquarters. The study participants (listed in the addendum) included a group of 18 university teachers and researchers (faculty fellows) who were present for the entire 10-week period and a larger group of attendees from universities, Government, and industry who came for a series of four 1-week workshops.

The organization of this report follows that of the summer study. *Space Resources* consists of a brief overview and four detailed technical volumes: (1) Scenarios; (2) Energy, Power, and Transport; (3) Materials; (4) Social Concerns. Although many of the included papers got their impetus from workshop discussions, most have been written since then, thus allowing the authors to base new applications on established information and tested technology. All these papers have been updated to include the authors' current work.

This volume—Materials—covers a number of technical and policy issues regarding the materials in space (mainly lunar and asteroidal) which can be used to support space operations. The first of the three parts of this volume discusses the nature and location of these materials, exploration strategy, evaluation criteria, and the technical means to collect or mine these materials. A baseline lunar mine and the basics of asteroid mining are presented and critiqued. The second part discusses the beneficiation of ores and the extraction of such materials as oxygen, metals, and the makings of concrete. The final part of the volume discusses the manufacturing and fabrication of nonterrestrial products. Considered are the economic tradeoffs between bringing needed products from Earth and making these products on location in space.

This is certainly not the first report to urge the utilization of space resources in the development of space activities. In fact, *Space Resources* may be seen as the third of a trilogy of NASA Special Publications reporting such ideas arising from similar studies. It has been preceded by *Space Settlements: A Design Study* (NASA SP-413) and *Space Resources and Space Settlements* (NASA SP-428).

And other, contemporaneous reports have responded to the same themes. The National Commission on Space, led by Thomas Paine, in *Pioneering the Space Frontier*, and the NASA task force led by astronaut Sally Ride, in *Leadership and America's Future in Space*, also emphasize expansion of the space infrastructure; more detailed exploration of the Moon, Mars, and asteroids; an early start on the development of the technology necessary for using space resources; and systematic development of the skills necessary for long-term human presence in space.

Our report does not represent any Government-authorized view or official NASA policy. NASA's official response to these challenging opportunities must be found in the reports of its Office of Exploration, which was established in 1987. That office's report, released in November 1989, of a 90-day study of possible plans for human exploration of the Moon and Mars is NASA's response to the new initiative proposed by President Bush on July 20, 1989, the 20th anniversary of the Apollo 11 landing on the Moon: "First, for the coming decade, for the 1990s, Space Station *Freedom*, our critical next step in all our space endeavors. And next, for the new century, back to the Moon, back to the future, and this time, back to stay. And then a journey into tomorrow, a journey to another planet, a manned mission to Mars." This report, *Space Resources*, offers substantiation for NASA's bid to carry out that new initiative.

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PART 1—Exploring, Evaluating, and Mining Nonterrestrial Resources

Richard E. Gertsch

The earliest writings on space industrialization recognized the need for materials to feed factories in orbit (O'Neill 1974; Johnson and Holbrow 1977; Billingham, Gilbreath, and O'Leary 1979). Transportation economics dictated (and still dictate) that the Earth cannot be the source of these materials. Recent writings (such as O'Leary 1983) have backed away from the concept of many large factories in orbit and concentrated instead on small, specific projects involving nonterrestrial materials.

Early large-scale thinking indicated that space manufacturing was economically favorable and could be a source of exciting new technologies. Space as a source of new wealth inspired dreams of capturing large asteroids, building Lagrangian industrial parks, and supplying cheap, plentiful products to a needy Earth. But industrial space parks represent a mature system and beg the question of how we get there. Given the expense of current space missions and our lack of deep space experience, moving directly to a mature system is not practical. A more circumspect scenario is needed. The early writers were not wrong, just premature; the question is, "What can we do tomorrow?"

While that question has not yet been answered, it has at least been formulated. One approach that has been suggested is to extract liquid oxygen from lunar materials and supply it to low Earth orbit (LOX to LEO) for use as spacecraft propellant (Davis 1983). Even if the idea never matures, it is an excellent starting point. In its mining and manufacturing activities, the project is modest, although it requires a significant jump in space transportation capability. It's specific, and it promises a return on investment. Much of this workshop's attention was focused on the LOX-to-LEO idea, although participants also recommended beginning an asteroid exploration program. The authors of the papers that follow concentrate on key practical problems in finding and exploiting the necessary raw materials, and they recommend solutions to these problems.

The members of our workshop group also considered some more advanced projects, such as a larger scale lunar base, capable of providing additional products. But, in the advanced scenarios, the group felt hampered by lack of problem definition. There was simply too little direction on types of products and project size. Terrestrial mining operations are driven by the market price of the product. Without such basic definitions, the group decided to concentrate on the LOX-to-LEO plan.

We discussed missions to retrieve material from asteroids that pass close to or cross the Earth's orbit. Although the difficulties in an asteroid mission appeared to be greater than those in a lunar mission, there also seemed to be no compelling reason why a modest mission could not qualify as a beginning effort in space resource exploitation. The sheer diversity of materials available from a single, small, Earth-approaching asteroid, along with the low ΔV required to retrieve such materials, warrants their consideration. The right asteroid could, in theory, supply most of the materials for a semi-closed space habitat, in addition to filling other industrial needs.

Comparing the LOX-to-LEO plan to the asteroid mission pointed up a basic dichotomy within our workshop group—a dichotomy of opinion as to what that first mission should be. Those experienced in the high-risk terrestrial mineral extraction business tend to favor the modest, specific LOX-to-LEO-type mission, arguing that risk should be minimized while we learn from and build on the first—small—lunar mining project. Those experienced in the basic sciences tend to favor the asteroid retrieval mission, arguing that the orbital mechanics to reach some asteroids are favorable and that the array of asteroidal materials is impressive. They admit, however, a current lack of information on specific asteroid targets, which must be addressed.

Another good example of the Moon-asteroid dichotomy is the question of the time value of money. The scientists in our group rightly pointed out that the transportation costs to the Moon and to the near-Earth asteroids are nearly equal, because the needed energy expenditures are similar. The mining industry representatives were concerned with the large time difference between the two missions; the round trip to the Moon takes about 2 weeks; to an asteroid, about 2 years. A lunar mine could begin producing almost immediately; an asteroid mine could not. This difference in time-to-production means that the capital amortization costs for a lunar mine would be much lower than those for an asteroidal mine. The time factor is a real and significant cost that must be repaid before a return on investment is realized. We note that an asteroid materials "pipeline" would overcome this problem, but such a pipeline is a part of a mature system, not of a startup enterprise. On the other hand, there may be compelling noneconomic reasons to ignore the time value of money (or other factors). Mineral operations on the Earth are occasionally operated at a loss in order to attain energy independence (Japan) or to obtain hard currency (Chile).

While our report on space mining and resource extraction favors the LOX-to-LEO or a similar lunar mission, we recommend that asteroid resource research be continued. Lunar exploitation may lead to exploitation of the asteroids from a cislunar staging area, using space manufacturing equipment and methods developed on the Moon. The Moon would then become a learning ground as well as a materials source. Or subsequent study of the lunar mining plan may show that asteroid retrieval is a superior mission, because particular resources are needed or a very favorable asteroid is found. In any case, projects like Earth-based asteroid watches and sample retrieval missions are justifiable on scientific grounds and are being included in NASA advanced planning scenarios. The data to be collected from these projects must be reviewed to ensure that they are appropriate to support mining enterprises.

To Build a Mine: Prospect to Product

Richard E. Gertsch

Developing Mineral Resources on Earth

The terrestrial definition of *ore* is "a quantity of earth materials containing a mineral that can be extracted at a profit." While a space-based resource-gathering operation may well be driven by other motives, such an operation should have the most favorable cost-benefit ratio possible. To this end, principles and procedures already tested by the stringent requirements of the profit motive should guide the selection, design, construction, and operation of a space-based mine. Proceeding from project initiation to a fully operational mine requires several interacting and overlapping steps, which are designed to facilitate the decision process and ensure economic viability (Baxter and Parks 1957, Pfleider 1972, Kuzvart and Bohmer 1978, Crawford and Hustrulid 1979, Church 1981).

Market Identification: Formulating the Project

All mineral extraction projects are market driven. The market determines product, project size, location, and extraction technology. The market will eventually determine all manner of project detail, such as distinguishing ore from waste. Questions such as possible products, product price, and infrastructure cost (e.g., power, labor, and transportation) must be answered. These answers provide an estimate of the scope of the projected mining operation and indicate reasonable geographic regions to explore. At this point, a regional exploration program can begin. Usually several regions to explore are identified and plans for the exploration of each region formulated.

Exploration: Finding Prospects

Regional exploration identifies specific mineral prospects within each region, which are then investigated in more detail. Large-scale regional exploration begins with historical studies. All references relating to the area, geology, markets, past production, etc., are researched. Concurrently or soon after, field work begins. Regional exploration tools include geochemical and geophysical remote sensing, aerial and satellite photography, stream sediment studies, studies of outcrops, and limited core drilling. In addition to the obvious geologic and mineralogic questions, many other factors enter into the picture: transportation needs, water supply, local labor force, local power supplies, equipment availability. Location of one or more properties that have passed the initial screening signals the end of regional exploration and the beginning of detailed site evaluation.

Site Evaluation: The Sampling Program

Even though local information on power, water, work force, roads, transportation, topographic relief, geologic factors, etc., continues to be collected and evaluated, the cornerstone of site investigation is the sampling program. While the immediate purpose of the sampling program is to delineate enough ore reserves to guarantee an economic mine, the quality of the program affects decisions made during the entire life of the mine. Geologic sampling takes many forms, but the most common tool by far is the core drill. Cores are taken at an interval small enough to sample accurately both ore reserves and any geologic formations that can affect mining operations. The depth and area of the core sampling program must represent the volume to be mined. While a minimum number of samples is required for a decision to start operations, sampling continues throughout the life of the mine.

Site Evaluation: The Ore Body Model

Ore body models are by far the major analytical tool used in the evaluation, design, and planning process. The importance of building as accurate a model as possible cannot be overstressed. The model itself is a mathematical representation of relevant subsurface and surface features: ore grades, amount of waste, geologic formations affecting mining, etc. This math model is derived from the data collected during the sampling program. Thus, sampling and modeling are related and concurrent processes. The model can be constructed in a variety of ways, from simple linear interpolation between samples (called "data points") to sophisticated variance-reduction geostatistical models. A modeling method may be selected because it worked well in the past. More than one model may be constructed, using one model to check the other. Regardless of the modeling method chosen, the influential factor in generating an accurate model is sampling interval and procedure.

The model allows the mine designer to plan the optimal mine, determine its profitability, and compare it to another property. The entire mining and milling operation is computer simulated over the life of the mine: different mining methods are tried; mill feed variation is calculated; production schedules are determined; sensitivity analyses are performed to determine the most important parameters for cost-effective operation. Over the life of the operation, data are collected and added to the model, and the model is continually updated and reanalyzed.

Design and Construction

The final model is no longer just a model of the ore body but a model of the entire project. Since the model determined economic viability, it is also the basis for mine design and production planning. The many design details are added, and the design is finished. As the design is completed, equipment and materials are ordered and construction begins. Design and planning continue throughout the entire mine life.

Implications for Nonterrestrial Resources

Presuming that the approach to developing nonterrestrial resources will parallel that for developing mineral resources on Earth, we can speculate on some of the problems associated with developing lunar and asteroidal resources. Even in the terrestrial case, the mine design and construction process is very complex. Much of the complexity results from the many unknowns in the process, which must be estimated from the data or in some cases guessed. As mineral sources, the Moon and the asteroids increase these unknowns by an order of magnitude.

The baseline for our study group was a small lunar mine and oxygen extraction facility. The facility would produce liquid oxygen (LOX) by electrostatically separating ilmenite from mined lunar soil and then reducing it to oxygen, iron, and titanium dioxide by a hydrogen reduction process. The production of 100 metric tons of lunar oxygen for delivery to low Earth orbit (LEO) implies production of an additional 300 metric tons for use in the Moon-LEO leg of the transportation system (200 to take 200 from the Moon to LEO; 100 of that 200 to bring hydrogen back to the Moon). This production requires that 40 000 metric tons of material be mined to supply the LOX feedstock. The mine and extraction facility would operate only during the lunar day (that is, 14 Earth days in operation, 14 off) throughout the year. Our study group considered only the problems that would be encountered in identifying the mining site, delineating the ore at the site, and building and operating the lunar mine, not those associated with the extraction facility or the technology.

Lunar Oxygen Plant

This plant is scaled to produce about 1000 metric tons of oxygen per year by extracting it from lunar ilmenite using hydrogen reduction. This figure is based on a design developed by Carbotek, Inc. In this conception, a front-end loader scoops up lunar soil from an open pit mine. The soil is carried by conveyor flights to a beneficiation plant, where the ilmenite is magnetically concentrated. The concentrated ilmenite is fed into a fluidized bed reactor, where the hydrogen extracts some of its oxygen as water. The water is then broken down by electrolysis, the oxygen is captured and stored cryogenically, and the hydrogen is recycled into the reactor. The unused portion of the lunar soil and the slag waste from the reduction process is finally transported to an old pit and used to fill it again.

To minimize the mining operation, the regolith should contain as much ilmenite as possible and the ilmenite should also be in a form (grain size and shape) which will allow concentration. Consequently, detailed evaluation of the potential mine site may be necessary before mining operations begin.

Artist: Pat Rawlings

Courtesy of Carbotek, Inc.

Most operating terrestrial mines have a very high rate of return (some on the order of 100 percent) merely to pay for finding and operating the ones that failed. Mining is a high risk business. Exploiting nonterrestrial resources will be even riskier; however, the returns in the long run may be much larger than for any single terrestrial mineral deposit.

The Market

While reasonable investigators have estimated nonterrestrial resource needs, so far no firm market, either product or quantity, has been identified. Meaningful detailed mine design and engineering work cannot begin until the market is better understood; however, the scenario presented by the LOX-to-LEO concept is useful in scoping a project. To produce and deliver to LEO the required 100 metric tons per year requires that 400 metric tons per year be produced on the Moon. There is also the possibility of producing bulk material and iron as byproducts for use on the Moon or in cislunar space. At this market size (which is a reasonable anticipation of the space transportation system requirements of a "business as usual" space program—see figure 1), the supply of lunar oxygen would offset transportation costs of approximately $600 000 000 per year for transporting oxygen from Earth to a space station using the Space Shuttle.

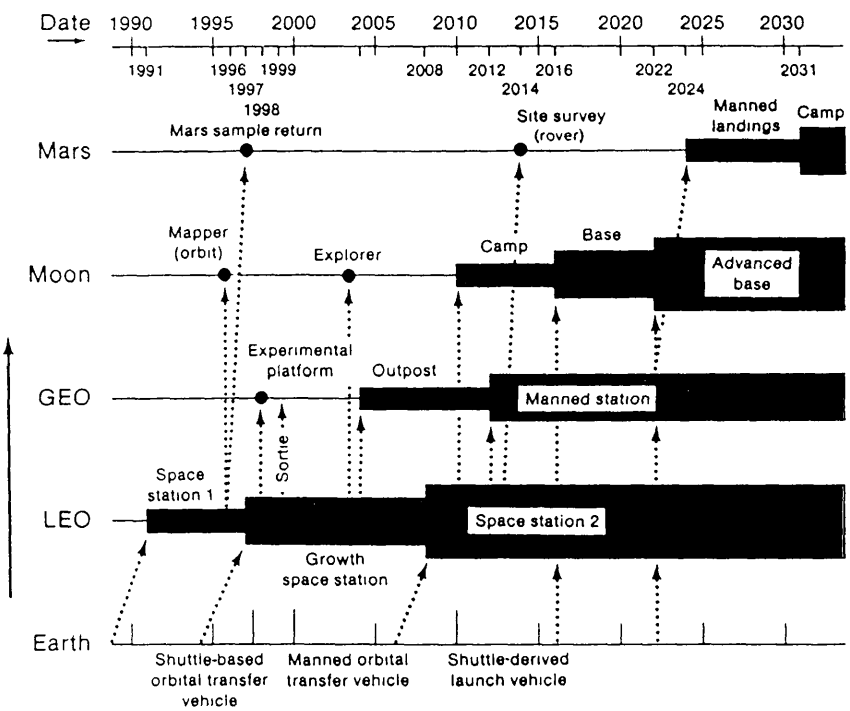


Figure 1

Baseline Scenario

If NASA continues its business as usual without a major increase in its budget and without using nonterrestrial resources as it expands into space, this is the development that might be expected in the next 25 to 50 years. The plan shows an orderly progression in manned missions from the initial space station in low Earth orbit (LEO) expected in the 1990s, through an outpost and an eventual space station in geosynchronous Earth orbit (GEO) (from 2004 to 2012), to a small lunar base in 2016, and eventually to a Mars landing in 2024. Unmanned precursor missions would include an experiment platform in GEO, lunar mapping and exploration by robot, a Mars sample return, and an automated site survey on Mars. This plan can be used as a baseline scenario against which other, more ambitious plans can be compared.

Exploration

Two classes of sites have been proposed for nonterrestrial resource development. For the LOX-to-LEO project, both the Moon and asteroids could be sources of oxygen; asteroids might provide different byproducts than the Moon would.

Apollo data show that ilmenite concentrations in basalts range from 3 to 20 percent at the investigated lunar mare sites. An Apollo site such as Apollo 11 or Apollo 17 is thus considered a prospect. The major problem with this statement is that the rest of the Moon might be ignored in favor of a few sites selected at the time of the Apollo Program. We don't know what we might be missing. One possible approach would be to build the Apollo-site mine and use it as a base to find prospects for other ilmenite mines or more ambitious mining projects. Another approach would be to complete a well-conceived exploration program before selecting a mine site. While far more expensive, this approach could yield better long-term results.

The asteroids are more problematical. No good compositional data have been obtained for appropriate Earth-approaching asteroids. While the probability is good that a favorable body exists, at present there is no asteroid "prospect" identifiable by terrestrial rules. Earth- or orbit-based asteroid watches may find promising bodies, but these bodies cannot be considered mining prospects until they have been physically sampled. Space mining is too risky and expensive to fly an asteroid retrieval mission solely on the basis of spectral and statistical data.

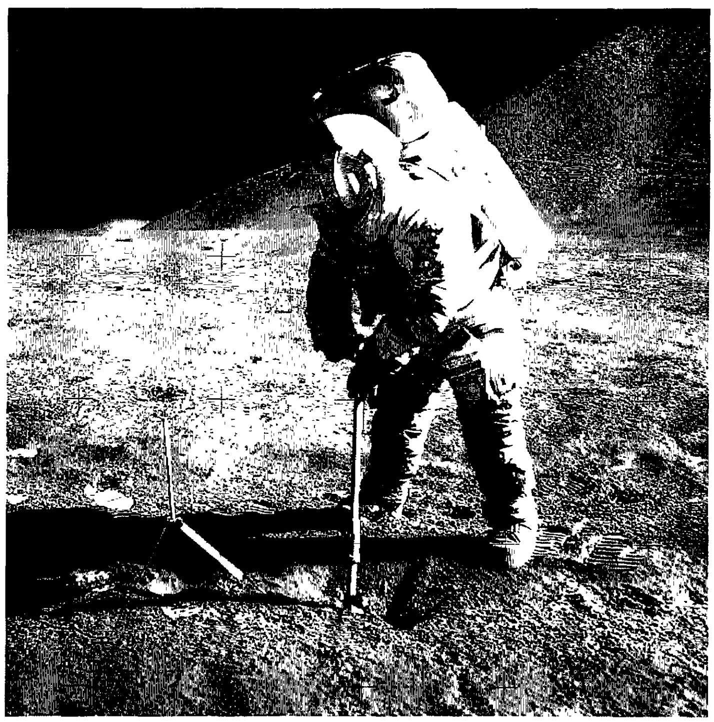
While we strongly support additional remote sensing missions such as the Lunar Observer* and asteroid watches as means to continue the exploration phase of nonterrestrial resource development, we doubt these programs will locate specific ore bodies. Terrestrial remote sensing programs rarely find mining prospects but have better success at locating areas of promise. Remote sensing from space has a relatively coarse resolution at mining scales and the interpretation of the resulting data consequently leaves many unknowns. It appears that these investigations will continue to be driven primarily by science considerations. But the instrument packages for space flights and the telescopes for asteroid search programs should be given close scrutiny as to data requirements and sensor resolution for mining purposes.

* The Lunar Observer is to be a lunar polar orbiter equipped to obtain geochemical data.

Sampling Program

Even before a sampling program that will support detailed mine modeling begins, a site may have enough supporting data to be considered a mining prospect. The best explored Apollo sites are characterized well enough to be considered mining prospects, particularly Apollo 17 for LOX-to-LEO. Assumptions may be made about the nature of the resources at these sites, and feasibility studies can begin. Such feasibility studies are a common and powerful tool in the mining industry, but they indicate that the major work on the prospect has just begun.

As a mining site, even Apollo 17 does not have nearly enough information to support mining operations. Questions such as grade variability, minable depth variability, and distribution of grain size (particularly oversized material) must be answered before mine and mill design can begin in earnest. The tool to answer these questions is the sampling program and ore body model. The Apollo sites were not sampled for the purpose of mining but for scientific inquiry. While it seems likely that the Moon is a fairly homogeneous body, there are not enough data even to predict the necessary sampling interval to build an accurate ore

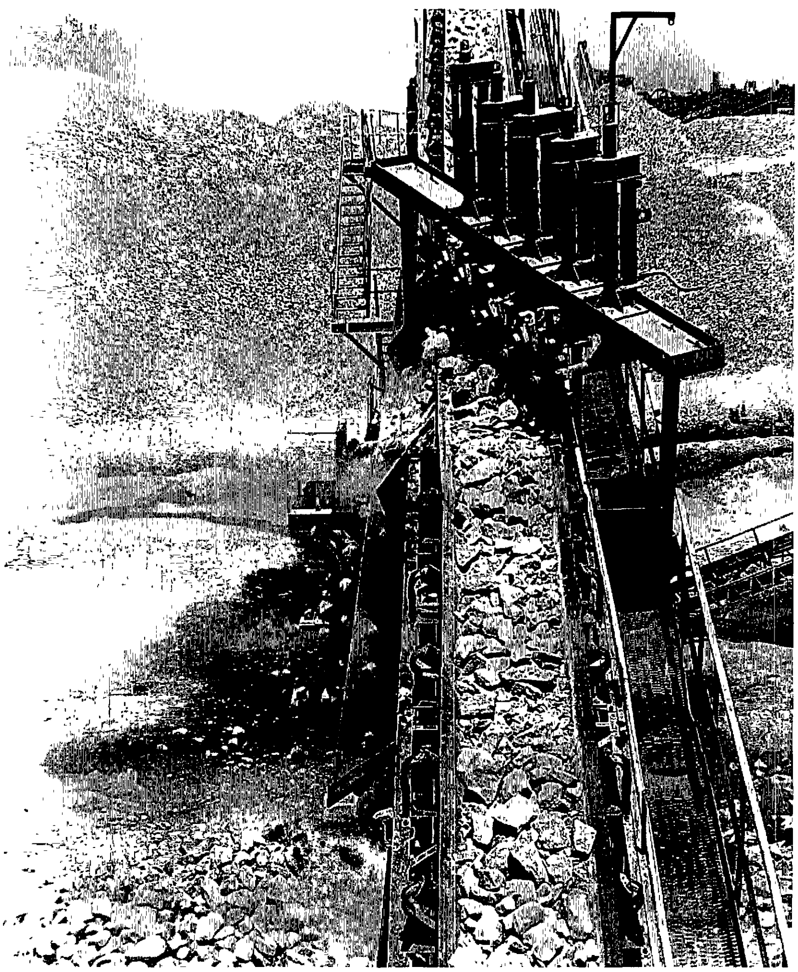


Apollo 15 Astronaut Taking a Core Sample of the Lunar Regolith

Apollo astronauts collected most samples by picking them up with tongs, a scoop, or a rake and bagging them for return to Earth. All rock samples were found as fragments or boulders in the lunar regolith (rock ground up by meteoroid impacts). A few cores were obtained. The longest, approximately 3 meters in length, were collected using a power drill. This one was obtained with a drive tube which was pushed or hammered into the regolith. Effective sampling for lunar resources will require more sophisticated drilling devices.

body model. Since the lunar samples cannot be adequately correlated with underlying bedrock, additional investigations will be required that can define the extent and thickness of the regolith to be mined.

Mine and mill operations must be designed to handle such variables as soil mineralization, grain size, and mining depth. For example, constant feed simplifies mill operation, making it more efficient. Oversized material must be rejected, preferably in the mining operation before it reaches the mill. The many factors affecting operations must be determined and characterized. Since the scale of these soil variables is unknown, the sample interval itself must be determined before the program is implemented.



Rejection of Oversized Material

A number of methods exist for sorting larger rocks and boulders from mined material The device shown here (Side-Kick by General Industries, Inc., Marietta, GA) automatically removes the larger rocks from a conveyor belt and collects them in a stockpile. The motion of the conveyor belt forces the rocks into several spoked wheels, placed at a predetermined angle to and a preset level above the oncoming conveyed materials. The rocks spin these wheels, causing the spokes of the wheels to kick these rocks over the side of the belt. Thus, the device works much like a diverting waterwheel in a stream. The kicked out rocks can be collected in a pile or a bin. A lunar version of this device could provide a selection of different sizes of rocks for use as paving and building stones as well as eliminating the larger rocks from the feedstock to be processed for oxygen or hydrogen.

For terrestrial mines, the cost of sampling is usually much lower than the cost of unexpected operational problems caused by failure to sample adequately. On the Moon even the best explored sites have far too little data to support operations. Thus, the quality of the lunar sampling program will directly reduce operational problems.

Mine Design and Construction

Even with limited data on prospective lunar mining sites, basic site characterization supplied by Apollo allows some generalized design work to begin. Integrating limited data with a few assumptions can yield a reasonable baseline lunar mining and milling operation.

The high cost of space transportation, especially of people, suggests that a lunar or asteroidal mine should be highly automated. But terrestrial mining industry experience with automation has been bleak. Mining operations, because they are complex, difficult, hard on equipment, and have many degrees of freedom, are poor candidates for automation. While systems like ventilation control, haulage trains, and equipment monitoring have been automated, no mine production system has ever been completely automated. Even though removing workers from a relatively dangerous environment seemed sufficient justification, production automation was too complex and unreliable to be economic. Present industry practice is driven solely by economics: Can money be saved by automating? The strategy is to automate a small, well-defined task and then do extensive debugging before automating another task. Given this poor record, automatic systems should be used with caution, have plenty of redundancy, and, if possible, have people present to solve the inevitable unexpected problems.

The automation trend does appear to be accelerating, however. The latest attempts are far more sophisticated and complex. For example, a Swedish firm has been experimenting with an automatic underground blast hole drilling rig. Underground blast hole drilling is a complex operation with many degrees of freedom and multilevel decision-making.

Our study group advises caution in automating lunar or asteroidal mining operations. Although it is possible that a completely automated mine would be less expensive than a similar manned operation, the issue is still in doubt and needs further study. We further note that a completely unmanned system is highly unlikely; no matter how well designed they are, automatic systems will eventually require human intervention. The basic tradeoff question is, "Would it be less expensive to develop an automated system or to accept the higher operating costs of a manned operation?" One more, important point should be made: The development of reliable automated mining systems would find a lucrative terrestrial market.

Recommendations

We recommend that several steps be taken to clarify the questions of lunar and asteroidal mining:

1. Determination of realistic markets for products from nonterrestrial resources is of major importance, because market income determines mine size, location, and mining and milling method—in short, the project.

2. Additional remote sensing by satellite for the Moon and by telescope and later spacecraft for asteroids should be done to provide a more robust data base on which to evaluate nonterrestrial resources.

3. Any remote sensing or onsite data-gathering projects must be evaluated for specific support of mining activities. Site information lowers costs.

4. Local sampling programs to determine the extent and minability of the deposits will still be necessary even after reconnaissance data have been gathered. These programs may combine surface sampling and sample return missions.

5. Technology for nonterrestrial mining must be studied in detail. Mining operations are notably difficult to automate and may ultimately require significant human intervention in the nonterrestrial case. The tradeoffs between manned and automated mining methods must be analyzed in detail and the best strategy selected. Error in either direction could result in the failure of the project.

6. Simplicity of equipment and mining method is a must for the first project gathering nonterrestrial materials. Reducing complexity will reduce development, capital, and operating costs.

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Lunar Exploration for Resource Utilization

Michael B. Duke

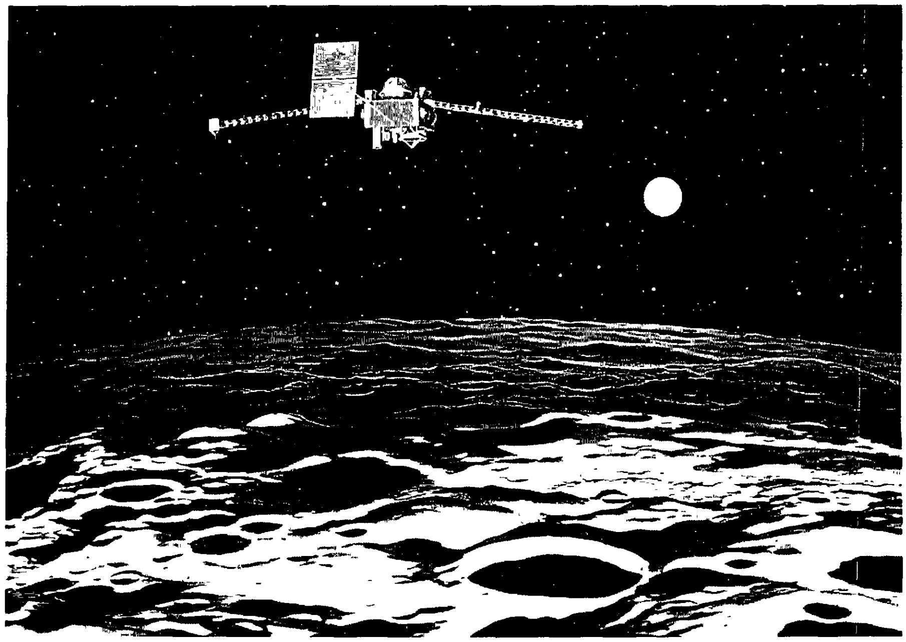
The strategy for developing resources on the Moon depends on the stage of space industrialization. A case is made, in part 3 of this volume, for first developing the resources needed to provide simple materials required in large quantities for space operations. Propellants, shielding, and structural materials fall into this category. As the enterprise grows, it will be feasible to develop additional resources—those more difficult to obtain or required in smaller quantities. Thus, the first materials processing on the Moon will probably take the abundant lunar regolith, extract from it major mineral or glass species, and do relatively simple chemical processing.

Little additional information on ore availability, beyond what was learned in the Apollo Program, is necessary to plan these early steps. Nevertheless, there are classes of information that need to be obtained before we actually develop lunar resources and a lunar base. We need to conduct a lunar remote sensing mission to determine the global distribution of features, geophysical properties, and composition of the Moon, information which will serve as the basis for detailed models of and engineering decisions about a lunar mine.

A satellite placed in low lunar polar orbit for a year or more can completely map the Moon in several ways. Such a mission, a lunar polar orbiter, has been proposed for 15 years, and the desirable complement of instruments for it is relatively well defined. See figure 2.

The combined data set from a lunar polar orbiter would serve to upgrade our understanding of the Moon and its geological evolution. The better we understand that evolution, the better we will be able to predict where to look for valuable resources.

The first contribution of such a mission would be to obtain additional images of the Moon, a process which was left incomplete by the Apollo Program. Past plans for lunar orbiters have not stressed high-resolution image data; however, such imagers have been proposed in more recent concepts of this mission. The instrument will probably be a charge-coupled device (CCD) imager.



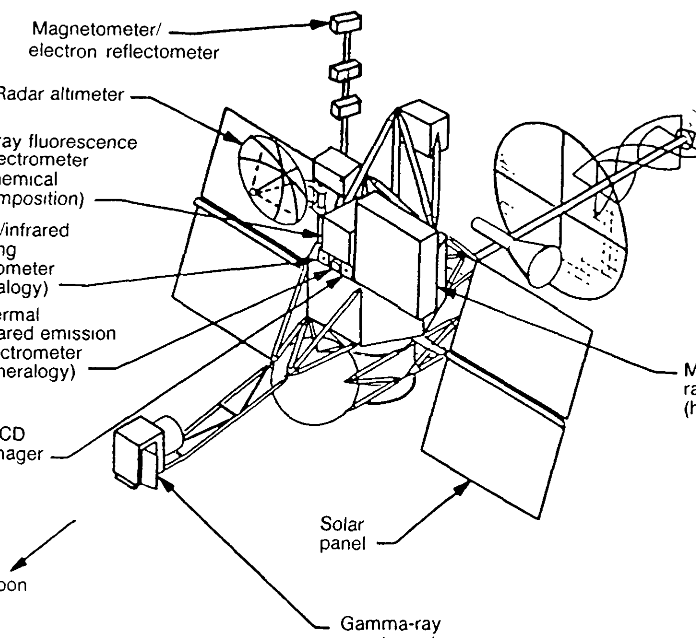


Figure 2

Lunar Observer

A spacecraft orbiting the Moon around its poles, the Lunar Observer, would map the chemical composition of the entire Moon, at a resolution of a few hundred meters. At that resolution, it will be possible to locate areas that are rich in particular lunar minerals, like ilmenite ($FeTiO_3$), and to check the idea that water ice may be trapped in polar cold spots. The Lunar Observer will improve general geological modeling of lunar resource distribution, but the presence of the lunar regolith, which has somewhat homogenized the uppermost surface, will make difficult the detection of specific ore bodies from lunar orbit. Besides such mining information, the Lunar Observer would also gather a broad range of useful scientific information.

Several geophysical instruments—a combination magnetometer and electron reflectometer, a radar (or laser) altimeter, and possibly a microwave radiometer—would gather important geophysical data.

Using x-ray and gamma-ray spectrometers, at a resolution of 1 to a few kilometers, this mission would provide a map of the chemical constituents of the lunar surface. If, as has been speculated, there are concentrations of water in permanently shadowed regions near the lunar poles, the gamma-ray device should be able to detect them. These data will provide information on the global distribution of rock and soil compositions but will not pinpoint small ore deposits, because the lunar regolith has been thoroughly mixed by eons of meteoroid bombardment.

A visible and infrared mapping spectrometer would take spectra of known points on the surface to provide mineralogical data at a finer scale. The results would be low-resolution spectral images of the surface. A thermal infrared emission spectrometer would gather spectra of a longer wavelength, which can be interpreted in terms of surface mineralogy of targeted points, but it would not produce images. This instrument might be upgraded to an imaging spectrometer if technology and costs allow its development.

Although the resolution of chemical mapping by a lunar orbiter may not be high, there are questions of site selection for a processing facility that can be addressed with orbiter data. For example, we know that there are titanium-rich basalts and soils and that there are likewise aluminum-rich anorthosites and soils. Our knowledge of where both types of materials can be accessed readily is less certain. If we plan to develop a lunar facility that depends on the availability of both titanium and aluminum, the lunar orbiter may be able to discover optimum locations.

Geochemical anomalies (ore bodies) may be difficult to locate directly with a lunar polar orbiter. However, some ore deposits may be related to geophysical irregularities. For example, there is a significant magnetic anomaly in the vicinity of the crater Reiner Gamma. The explanation of the anomaly is not in hand, but further exploration of it and similar anomalies, if they are found, may lead to the discovery of new resources. In general, the correlation of chemical and geophysical data should be pursued.

There are a number of issues related to the operation of a lunar base and its resource extraction facilities for which additional image information would be desirable. These include questions of engineering feasibility, surface trafficability, safety, ease of working with the regolith, availability of slopes, and soil cohesiveness. As part of a lunar polar orbiter mission, images with resolution of a few meters should be obtained for areas under consideration as sites for lunar bases.

A lunar orbiter can provide information to establish the surface characteristics of the Moon before extensive human activities there. Because of the static nature of the lunar surface under natural conditions, human activity on the Moon will inevitably change the environment. It will be important to obtain global maps before that stage of development, both to serve as a baseline for further survey work and to record a state that will be changed irreversibly.

Lunar Material Resources: An Overview*

James L. Carter

Abstract

The analysis of returned lunar samples and a comparison of the physical and chemical processes operating on the Moon and on the Earth provide a basis for predicting both the possible types of material resources (especially minerals and rocks) and the physical characteristics of ore deposits potentially available on the Moon. The lack of free water on the Moon eliminates the classes of ore deposits that are most exploitable on Earth, namely, (a) hydrothermal, (b) secondary mobilization and enrichment, (c) precipitation from a body of water, and (d) placer.

The types of lunar materials available for exploitation are whole rocks and their contained minerals, regolith, fumarolic and vapor deposits, and nonlunar materials, including solar wind implantations. Early exploitation of lunar material resources will be primarily the use of regolith materials for bulk shielding; the extraction from regolith fines of igneous minerals such as plagioclase feldspars and ilmenite for the production of oxygen, structural metals, and water; and possibly the separation from regolith fines of solar-wind-implanted volatiles. The only element, compound, or mineral that by itself has been identified as having the economic potential for mining, processing, and return to Earth is helium-3.

Introduction

To be economical, a lunar base operation requires the identification, characterization, development, and utilization of local resources (Flawn 1966, Dalton and Hohmann 1972, Criswell 1980, Haskin 1983, Carter 1985). Even though it is romantic to dream about exotic and fabulously rich mineral deposits, history has shown us repeatedly that in any area the natural resources that are exploited first are those that (a) are needed for basic survival, (b) are readily available, and (c) can be used with the least modification. Ore deposits that are remote, mineralogically complex, or low grade (and therefore must be dealt with in large volume) are not exploited until after the infrastructure necessary for their exploitation can be constructed. Meeting the criteria for early exploitation is material from the lunar regolith, the layer of debris that covers the surface of the lunar bedrock. Such material can be used as is for bulk shielding to reduce cosmic ray exposure. And from the lunar regolith such desirable elements as oxygen and iron can be extracted without extensive processing such as crushing. The ideal situation ultimately will be to use the lunar regolith material as a feedstock and to separate from it numerous

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elements and products (Lindstrom and Haskin 1979), but this requires an extensive infrastructure of sophisticated and elaborate processing equipment (Williams et al. 1979).

In this paper I develop a general overview of what can be inferred from theoretical considerations of the physical and chemical processes operating on the Moon and what is known about possibly available types of lunar materials from analysis of samples returned by the Apollo and Luna missions. My overview will include an evaluation of lunar regolith fines (the less-than-1-mm fraction) as a source of volatile elements.

Physical and Chemical Processes

Comparison of physical and chemical processes operating on the Earth and on the Moon provides a basis for predicting both the possible types of material resources, especially minerals, and the physical characteristics of ore deposits potentially available for exploitation on the Moon.

Active Surface Agents

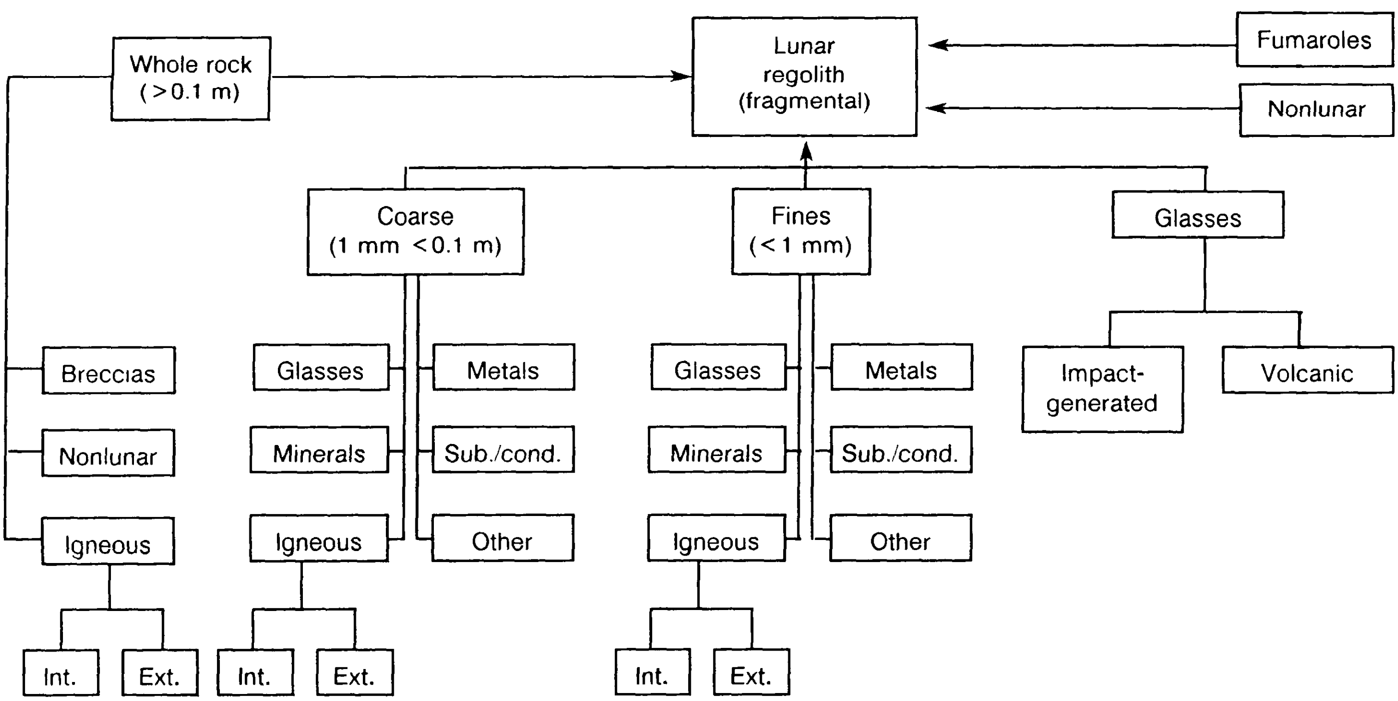
One approach to evaluating possible lunar material resources is to compare the active surface agents that affect the Earth and the Moon. These are listed in table 1. The most striking feature described in table 1 is that the Moon has no atmosphere. Therefore, it has (a) no free water (and thus no freeze/thaw cycles and few, if any, water-bearing minerals such as clays), (b) no free oxygen (and thus no oxidation), and, most importantly, (c) no biological activity. The major physical (erosional) and chemical (weathering) agents—water and oxygen, respectively—and the resulting products we are familiar with on Earth play no role in shaping the surface of the Moon and thus they play no role in the formation of potential lunar ore deposits. The only indigenous lunar erosional agent is volcanic, especially basaltic, lava flows (Hulme 1973). The extremely low viscosities and thus the high extrusion rates of lunar basaltic lava flows (Moore and Schaber 1975) are conditions favorable for the formation of lava channels and tubes, which are very abundant on the lunar surface (Oberbeck et al. 1971). It may be possible to use the naturally sheltered environment of a large lava tube as housing for a lunar base (Hörz 1985). Moreover, some lava tubes may contain accumulations of volatiles.

TABLE 1. *Comparison of Active Surface Agents on the Earth and on the Moon*

Process	Agents		Type	Earth	Moon
ENDOGENIC	Atmosphere	H_2O	Free	Yes (major)	No? (transient)
		O_2	"	Yes (major)	No? (transient)
		CO_2	"	Yes	Yes? (transient)
		H_2	"	Yes (v minor)	Yes (v. minor) (transient)
		S	"	Yes?	Yes (v. minor) (transient)
		Others	"	Yes	Yes? (transient)
	Liquid water			Yes (major)	No
	Volcanic	Solids		Yes (major)	Yes (minor?)
		Liquids		Yes (major)	Yes (major)
		Gases		Yes (minor)	Yes (v. minor)
	Thermal	Freeze/thaw		Yes (major)	No
		No water		Yes? (v. minor)	Yes (v. minor?)
	Biological			Yes (major)	No
	Gravity			Yes (major)	Yes (minor)
EXOGENIC	Solar wind			No	Yes (major)
	Impact-produced	Solids: Micro. met.		No?	Yes (major)
		Solids: Macro. met		Yes (v minor)	Yes (major)
		Liquids: Micro. met.		No	Yes (major)
		Liquids: Macro. met		Yes (v. minor)	Yes (major)
		Gases: Micro. met.		No?	Yes (minor)
		Gases: Macro. met.		Yes (v. minor)	Yes (major)

The lack of an atmosphere on the Moon allows meteorites, comets, micrometeorites, and the solar wind to bombard the lunar surface unimpeded. These are the most important agents shaping the lunar surface. They also contribute to its material resources (table 2; see also Williams and Jadwick 1980).

TABLE 2. *Types of Lunar (Mare, Highland, Other) Materials Resources*



Cond. = condensates
Ext. = extrusive
Int. = intrusive
Sub. = sublimates

The various types of materials that contribute to the lunar regolith are diagrammatically displayed in table 2. To reveal the exploitation potential of the contents of any box requires much additional information. Also of importance is the distribution of the various types of lunar materials. From the simplest point of view, the Moon has two basic types of physiographic provinces: light-colored lunar highlands and dark-colored lunar maria. The highlands are old crust (more than four billion years). The maria are relatively young (less than four billion years) and are large impact-produced craters that are flooded with basaltic rock types (Taylor 1975).

The chemistry of these two basic physiographic provinces is similar, except in aluminum, iron, calcium, and titanium (table 3), but their mineralogy is quite different. The highlands consist of rocks very rich in plagioclase and thus rich in aluminum and calcium; whereas, the maria consist of ilmenite-bearing basaltic rocks and thus are titanium- and iron-rich. The ideal early exploitation target would be situated where both types of materials are juxtaposed, such as near the margins of some mare (McKay and Williams 1979) or on a ray from a major impact that extends from the lunar highlands into a mare.

TABLE 3. *Average Major Element Chemistry for Mare and Highland Soil*
[From Turkevich 1973]

Element	Percent of atoms			Weight percent of oxides		
	Mare	Highland	Average surface	Mare	Highland	Average surface
O	60.3 ± 0.4	61.1 ± 0.9	60.9			
Na	0.4 ± 0.1	0.4 ± 0.1	0.4	0.6	0.6	0 6
Mg	5.1 ± 1.1	4.0 ± 0.8	4 2	9.2	7 5	7 8
Al	6.5 ± 0.6	10.1 ± 0.9	9.4	14.9	24.0	22.2
Si	16.9 ± 1.0	16.3 ± 1.0	16.4	45.4	45.5	45.5
Ca	4.7 ± 0.4	6.1 ± 0.6	5.8	11.8	15.9	15.0
Ti	1.1 ± 0.6	0.15 ± 0.08	0.3	3.9	0.6	1.3
Fe	4.4 ± 0.7	1.8 ± 0.3	2.3	14.1	5.9	7.5

Rock Cycle

Another approach to evaluating possible lunar material resources is to compare the rock cycle of the Moon (fig. 3) to that of the Earth (fig. 4). A rock cycle is a sequence of events leading to the formation, alteration, destruction, and reformation of rocks as a result of various physical and chemical processes. Thus, it is a pictorial way of viewing the different processes that lead to natural material resources such as ore deposits and of predicting the types of deposits that result from the various physical and chemical processes. A comparison of the Moon's rock cycle with the Earth's (shown in figures 3 and 4, respectively) reveals the

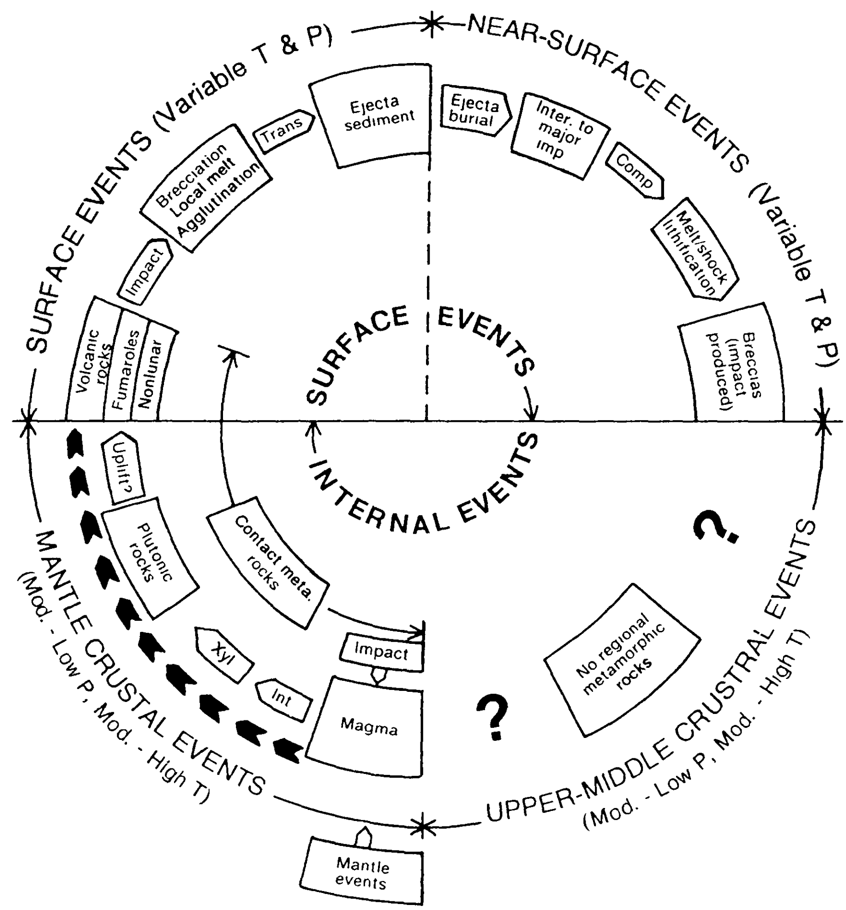


Figure 3

Moon Rock Cycle

Comp. = compression
Imp. = impact
Int. = intrusion
Inter. = intermediate
Meta = metamorphic
Mod = moderate
Trans = transport
Xyl. = crystallization

fundamental differences resulting from the lack of free water and oxygen on the Moon. The comparison also shows that, while the Moon has been dominated by external processes, the Earth has been dominated by internal processes. The various types of physical and chemical processes represented by the rock cycles, the resulting commercial types of mineral deposits on Earth, and the probable types of lunar deposits are shown in table 4.

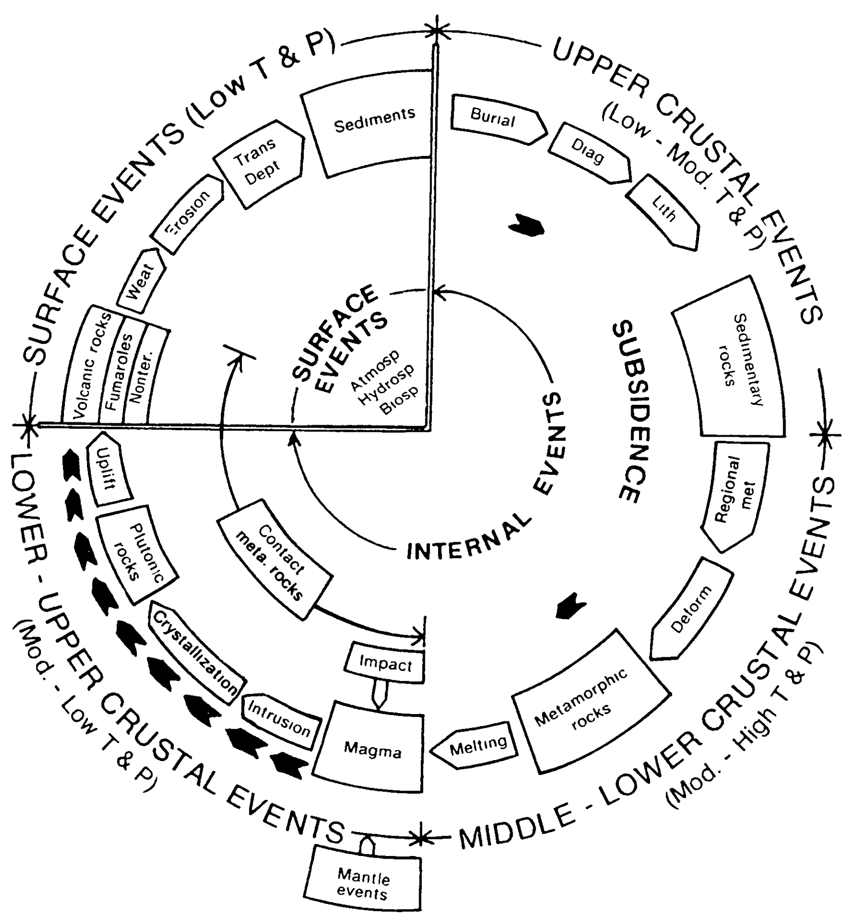


Figure 4

Earth Rock Cycle

Atmosp. = atmospheric
Biosp. = biospheric
Deform. = deformation
Dept. = deposition
Diag. = diagenesis
Hydrosp. = hydrospheric
Lith. = lithification
Met = metamorphism
Meta. = metamorphic
Nonter. = nonterrestrial
Trans. = transport
Weat. = weathering

TABLE 4. *Various Processes in Mineral Deposit Formation*

Type	Probably occur on Moon	Commercial type Earth deposit	Probable type lunar deposit
I. Igneous			
A. Intrusive magmatic			
1. Early			
a. Dissemination	Yes	Diamonds, apatite, corundum	Ilmenite
b. Segregation	Yes	Chromite, Pt, anorthite, ilmenite, titanomagnetite	Ilmenite, anorthite, chromite?
c. Injection	Yes?	Magnetite	Oxides?
2. Late			
a. Gravitative liquid accumulation			
i. Seg.	Yes	Chromite, Pt, titanomagnetite	Ilmenite, titanomagnetite?
ii. Inject.	Yes?	Magnetite, apatite	Oxides?
b. Immiscible liquid			
i. Seg.	Yes	(Ni,Cu)S, Pt, Au	(Ni,Cu,Fe)S, Pt, Au?
ii. Inject.	Yes	(Ni,Cu)S, Pt	(Ni,Cu,Fe)S, Pt
c. Carbonatite	No?	Rare earths	?
d. Felsic pegmatite	No?	Feldspar, mica, rare earths, quartz, gemstones	?
B. Volcanic			
1. Glass	Yes	Perlite, pumice	Ti-, Al-rich
2. Submarine exhalative	No	Base metal	None
3. Sublimates; condensates	Yes	S, NaCl	S?, chlorides
II. Metamorphic/metasomatic			
A. Contact	Yes	W, Cu, Pb, Zn	?
B. Regional	No?	Abrasives, aluminosilicates	None?
C. Thick ejecta blanket	Yes	Meteoritic material	Phosphates, volatiles?
III. Surficial (sedimentation)			
A. Sedimentation	Yes	Sand, gravel, limestone	Regolith
B. Biochemical processes; organic accumulations	No	Petroleum	None
C. Oxidation; supergene enrichment	No	Base metal, Au, Ag, U	None
D. Residual/mechanical concentration	No?	Au, rare earths, Al, Fe, diamonds	None?
E. Evaporation	No?	Salts	None?
F. Groundwater	No?	U, Cu	None?
IV. Asteroid/comet impact	Yes	Ni, Fe, Pt?	Ni, Fe, Pt, C, H_2O, chlorides

The apparent lack of plate tectonics operating on the Moon (Taylor 1975) is also of importance in evaluating possible lunar material resources. Plate tectonics, which is characterized on Earth by a small number of large, broad crustal plates, each of which "floats" on a viscous underlayer (mantle) and moves more or less independently of the others, is fundamental to the development of most commercial type ore deposits and even petroleum deposits on Earth (Mitchell and Garson 1981, Hutchison 1983). One important aspect of plate tectonics on the Earth is the recycling and partial fusion of crustal materials to form granites and their related ore deposits and pegmatites (Mitchell and Garson 1981, Hutchison 1983). Even though a granite-like residual phase (mesostasis and "veinlets") and very small granitic clasts in breccias occur in rocks on the Moon (Rutherford et al. 1976, Warren et al. 1983a), there is no evidence that large-scale granitic bodies occur on the Moon (Taylor 1975). Moreover, unlike the majority of similar Earth rocks, the granite-like Moon rocks are completely devoid of hydrous phases (Warren et al. 1983a).

Lunar Material Resources

The types of lunar materials available for exploitation (table 2) can be grouped into four basic categories: whole rocks and minerals, regolith, fumarolic and vapor deposits, and nonlunar materials. We have very little direct knowledge of whole rocks in situ, and we know virtually nothing about possible fumarolic deposits. The Apollo and Luna missions were designed to study the lunar regolith, with cores taken a maximum of 3 meters deep (Carrier 1974, Taylor 1975). Thus, in the subsequent sections, I will mainly discuss the potential of the near-surface lunar regolith as a source of materials, especially as a source of volatile elements.

Rocks and Minerals

Rocks: The major rock types in the maria are basalts, gabbros, pyroxene-rich peridotites, and breccias (Mason and Melson 1970, Levinson and Taylor 1971, Taylor 1975, Gillett 1983, Taylor 1984). The major rock types in the highlands are various types of anorthosites; anorthositic gabbros;

KREEP basalt enriched in potassium, rare earths, and associated elements; low-potassium basalt; norite; dunite; and breccias (Taylor 1975, Gillett 1983).

The mare rock types are composed primarily of plagioclase feldspars, clinopyroxenes, and ilmenite, with minor olivine, chromite/ulvöspinel, and tridymite/cristobalite (Taylor 1975). The highland rock types are composed primarily of plagioclase feldspars, orthopyroxenes, and olivine, along with minor ilmenite (Taylor 1975). The whole rocks represent a potential source of these minerals and someday may be used as a feedstock because they would supply material of relatively uniform physical characteristics, but their use would require an extensive infrastructure for mining and processing. The regolith fines will probably be exploited first because they have already been pulverized by meteoritic and cometary bombardment. The ranges of modal abundances for the major lunar minerals in various rock types are shown in table 5. The ranges of chemical compositions for the major lunar minerals in various rock types are shown in table 6.

TABLE 5. *Ranges of Modal Abundances (Volume %) for the Major Lunar Minerals in Various Rock Types*
[Modified from Waldron, Erstfeld, and Criswell 1979]

	High-Ti mare basalts	Low-Ti mare basalts	Highland rocks
Pyroxene	42 - 60	42 - 60	5 - 35
Olivine	0 - 10	0 - 36	0 - 35
Plagioclase	15 - 33	17 - 33	45 - 95
Opaques (mostly ilmenite)	10 - 34	1 - 11	0 - 5

TABLE 6. *Ranges of Chemical Compositions for the Major Lunar Minerals in Various Rock Types*
[Modified from Waldron, Erstfeld, and Criswell 1979]

Components (wt. %)	Pyroxene	Olivine	Plagioclase	Opaques (mostly ilmenite)
		a. High-titanium mare basalts		
SiO_2	44.1 - 53.8	29.2 - 38.6	46.9 - 53.3	< 1.0
Al_2O_3	0.6 - 6.0		28.9 - 34.5	< 2.0
TiO_2	0.7 - 6.0			52.1 - 74.0
Cr_2O_3	< 0.7	0.1 - 0.2		0.4 - 2.2
FeO	8.1 - 45.8	25.4 - 28.8	0.3 - 1.4	14.9 - 45.7
MnO	< 0.7	0.2 - 0.3		< 1.0
MgO	1.7 - 22.8	33.5 - 36.5	< 0.3	0.7 - 8.6
CaO	3.7 - 20.7	0.2 - 0.3	14.3 - 18.6	< 1.0
Na_2O	< 0.2		0.7 - 2.7	
K_2O			< 0.4	
		b. Low-titanium mare basalts		
SiO_2	41.2 - 54.0	33.5 - 38.1	44.4 - 48.2	< 1.0
Al_2O_3	0.6 - 11.9		32.0 - 35.2	0.1 - 1.2
TiO_2	0.2 - 3.0			50.7 - 53.9
Cr_2O_3	< 1.5	0.3 - 0.7		0.2 - 0.8
FeO	13.1 - 45.5	21.1 - 47.2	0.4 - 2.6	44.1 - 46.8
MnO	< 0.6	0.1 - 0.4		0.3 - 0.5
MgO	0.3 - 26.3	18.5 - 39.2	0.1 - 1.2	0.1 - 2.3
CaO	2.0 - 16.9	< 0.3	16.9 - 19.2	< 1.0
Na_2O	< 0.1		0.1 - 1.3	
K_2O			< 0.3	
		c. Highland rocks		
SiO_2	51.10 - 55.4	37.70 - 39.9	44.00 - 48.0	< 0.1
Al_2O_3	1.00 - 2.5	< 0.1	32.00 - 36.0	0.80 - 65.0
TiO_2	0.45 - 1.3	< 0.1	0.02 - 0.03	0.40 - 53.0
Cr_2O_3	0.30 - 0.7	< 0.1	< 0.02	0.40 - 4.0
FeO	8.20 - 24.0	13.40 - 27.3	0.18 - 0.34	11.60 - 36.0
MgO	16.70 - 30.9	33.40 - 45.5	< 0.18	7.70 - 20.0
CaO	1.90 - 16.7	0.20 - 0.3	19.00 - 20.0	< 0.6
Na_2O			0.20 - 0.6	
K_2O			0.03 - 0.15	

Minerals: The number of mineral species positively identified on the Moon is 70, with 14 others tentatively identified (table 7) (Levinson and Taylor 1971, Frondel 1975, Warren et al. 1983b, Meyer and Yang 1988), which is less than 2 percent of the mineral species known on Earth (Fleischer 1987). However, less than 2 percent of the 3800 mineral species known on Earth makes up more than 95 percent of the commercially exploitable mineral deposits on Earth. These may be divided into those that can be used in their natural state, either singularly or combined with others to form a rock, and those that must be refined. Of the known lunar minerals, a maximum of one-sixth have "early" exploitation potential These are apatite, armalcolite, chromite, "goethite," ilmenite, iron-nickel, olivine, plagioclase feldspars, potassium feldspars, and whitlockite (table 7). But of these only ilmenite, plagioclase feldspars,

TABLE 7. *Lunar Minerals*

Common and abundant minerals		Important accessory minerals	
Clinopyroxenes	$(Ca,Mg,Fe)_2Si_2O_6$	Apatite	$Ca_5(PO_4)_3(F,Cl)$
Augite		Armalcolite	$(Fe,Mg)Ti_2O_5$
Ferroaugite		Baddeleyite	ZrO_2
Ferrohedenbergite		Cristobalite	SiO_2
Ferropigeonite		Iron-nickel	FeNi
Pigeonite		Kamacite	
Salite		Taenite	
Subcalcic augite		Potassium feldspars	$KAlSi_3O_8$
Titanaugite		Hyalophane	
Ilmenite	$FeTiO_3$	Orthoclase	
Olivine	$(Mg,Fe)_2SiO_4$	Sanadine	
Chrysolite		Pyroxferroite	$CaFe_6(SiO_3)_7$
Fayalite		Quartz	SiO_2
Forsterite		Spinels	$(Fe,Mg,Ti)(Al,Cr,Ti)_2O_4$
Orthopyroxenes	$(Mg,Fe)SiO_3$	Chromite	
Bronzite		Picotite	
Enstatite		Pleonaste	
Hypersthene		Hercynite	
Plagioclase feldspars	$(Ca,Na)Al_2Si_2O_8$	Spinel	
Andesine		Titanian chromite	
Anorthite		Tranquillityite	$Fe_8(Zr,Y)_2Ti_3Si_3O_{24}$
Bytownite		Tridymite	SiO_2
Labradorite		Troilite	FeS
		Ulvospinel	Fe_2TiO_4
		Whitlockite	$Ca_9MgH(PO_4)_7$
		Zirkelite	$(Ca,Fe)(Zr,Ti)_2O_7$

TABLE 7 *(concluded)*.

Rare minerals	
Aluminum carbide	Al_4C_3
Amphibole	
Hornblende	
	$(Ca,Na,K)_{2\text{-}3}(Mg,Fe,Al)_5\ ([OH]?,F,Cl)_2\ Al_2Si_6O_{22}$
Magnesioarfvedsonite	
	$(Na,K,Ca)_3(Mg,Mn,Fe)_5\ ([OH]?,F)_2\ (Si,Al,Ti)_8O_{22}$
Bornite	Cu_5FeS_4
Brass	CuZn
Calcite (?)	$CaCO_3$
Chalcopyrite	$CuFeS_2$
Cohenite	$(Fe,Ni)_3C$
Copper	Cu
Corundum	Al_2O_3
Cubanite	$CuFe_2S_3$
Garnet	
Almandine	$Fe_3Al_2(SiO_4)_3$
"Goethite"	FeOOH
Akaganeite	
Lepidochrosite	
Lawrencite	$FeCl_2$
Mackinawite	FeS
Mica	
Biotite	
	$K_2([OH]?,F)_4\ (Mg,Fe,Al)_6\ (Si,Al)_8O_{20}$
Muscovite (?)	
	$KAl_2(AlSi_3)\ O_{10}([OH]?,F)_2$
Monazite	$(Ca,La,Y,Th)PO_4$
Niningerite	MgS
Pyrochlore	
Yttrobetafite	
	$(Ca,Y,REE,Fe,Pb,Th,U)_2\ (Ti,Nb,Fe)_2O_7$
Rutile	TiO_2
Schreibersite	$(Fe,Ni,Co)_3P$
Sphalerite	ZnS
Thorite	$ThSiO_4$
Tin	Sn
Titanite	$CaTiSiO_5$
Zircon	$ZrSiO_4$
Tentative minerals	
Aragonite	$CaCO_3$
Farringtonite	$(Mg,Fe)_3(PO_4)_2$
Garnet	
Spessartite	$Mn_3Al_2(SiO_4)_3$
Hematite	Fe_2O_3
Magnetite	Fe_3O_4
Melilite	
	$(Ca,Na)_2(Mg,Fe)(Al,Si)_2O_7$
Moissanite	SiC
Nickel	Ni
"Nickel silver"	CuNiZnFe
Pentlandite	$(Fe,Ni)_9S_8$
Perovskite	$CaTiO_3$
Sillimanite (or mullite)	Al_2SiO_5
Talnakhite	$Cu_9(Fe,Ni)_9S_{16}$
Wustite	FeO

and possibly "goethite" are very likely to be exploited early (McKay and Williams 1979). These minerals could be used to produce oxygen, structural metals (aluminum, iron, and titanium), and water, and they seem to occur in concentrations high enough to warrant exploitation. Apatite, potassium feldspars, and whitlockite are important raw materials in the production of fertilizers for growing plants on the Moon, but they may not be present in high enough concentrations to be easily exploited.

Regolith

The lunar regolith, especially the fraction called "fines" (the particles that are less than 1 mm in diameter), offers the opportunity to take advantage of two different physical processes operating on the lunar surface: (1) brecciation, including pulverization through meteoritic and cometary impact, and (2) solar wind implantation of volatile species. The longer the lunar regolith is exposed to bombardment, the greater the extent of pulverization and implantation of volatile species. However, two counterproductive processes are in operation. First, major impacts result in throw-out of large volumes of material that cover up older regolith. Second, micrometeorite bombardment results in production of agglutinates, which are lunar fines welded together with liquid silicate (glass) (McKay et al. 1971). Thus, there are both destructive and constructive processes operating on the lunar surface.

The heating of the fines associated with micrometeoritic events liberates some of the solar-wind-implanted volatile species (Carter 1985) and plays an important role in the distribution and redistribution of volatiles on the Moon (Wegmüller et al. 1980).

The formation of agglutinates also decreases the availability of minerals, such as plagioclase feldspars and to a lesser extent ilmenite, for concentration from lunar fines (tables 8 and 9; figure 5). But agglutination does produce a small amount of metallic iron (Morris 1980), which should be concentratable by magnetic means. There is, in any case, an upper limit for production of agglutinates (McKay and Basu 1983). The ideal situation would be to have lunar regolith old enough to allow maximum solar wind implantation but not so old as to allow extensive production of agglutinates.

TABLE 8. *Grain Populations in Percent for Selected Particle Types of the 90-150 Micrometer Size Fraction in Some Apollo 16 Soils*
[From McKay and Williams 1979]

	Sample	Plagioclase	Anorthosite	Light matrix breccia	Total	Normative anorthite	Agglutinates
Core	60009,455	47.0	6.8	3.8	57.6	82	12.5
	60009,457	76.2	3.8	0.8	80.8	---	2.2
	61161	14.7	4.7	13.6	33.0	72	37.0
STA 1	61181	5.3	4.3	7.3	16.9	74	59.6
	61221	17.0	13.6	10.0	40.6	77	6.3
	61241	12.3	5.0	18.3	35.6	74	27.1
STA 2	62281	16.0	5.6	11.3	32.9	73	40.0
	63321	9.6	11.2	14.0	34.8	79	32 6
STA 3	63341	12.6	5.9	14.9	33.4	79	40.0
	63501	10.3	3.0	16.7	30.0	76	44 6
STA 4	64501	20.3	3.0	6.6	29.9	75	51.6
STA 8	68501	12.3	1.9	29.3	43.5	73	38 6
	67481	15.0	10.9	20.3	45.2	79	23.0
	67601	14 0	3.6	24 0	41.6	79	36.0
STA 11	67701	21 0	3.3	34.0	58.3	78	15.6
	67711	41.0	4.6	36.6	82 2	80	1.6

TABLE 9. *Modal and Normative Ilmenite in Mare Basalts From the Apollo Missions*
[From McKay and Williams 1979]

Sample	Modal ilmenite content, %	Normative ilmenite content, %
10003	14-18	21.5
10017	14-24	22.4
10044	6-12	17.1
10045	7-11	21.3
10049	16-17	21.5
10072	13-22	22.8
Apollo 11 mean	**14.5**	**21.1**
12202	8-11	4.9
12012	5-12	6.6
12022	9-23	9.3
12039	8-10	5.7
12051	8-11	8.9
12063	8-10	9.5
Apollo 12 mean	**10**	**7.5**
15016	6	4.4
15076	0.5	3.6
15475	1.0	3.4
15555	1-5	4.0
15556	2	5.1
Apollo 15 mean	**2.6**	**4.1**
75055	12-20	20.5
70215	13-37	24.7
70035	15-24	24.7
70017	19-23	24.7
Apollo 17 mean	**20.4**	**23.7**

Minerals: The constant meteoritic and cometary bombardment of the lunar surface results in comminution of whole rocks, with liberation of the mineral constituents. Most of the minerals listed in table 7 have been found as isolated grains or as composite particles in the lunar regolith fines. The available anorthite content in the Apollo 16 lunar highland regolith samples (90- to 150-micrometer size fraction) varies from just under 17 percent to just over 82 percent (see table 8) and averages 43.5 percent. The lower values result from the inverse relationship between available anorthite content and agglutinate content (see figure 5). The ilmenite content of mare basalts from all Apollo missions varies from 0.5 percent to 37 percent (see table 9) and averages 11.5 percent. If the significantly lower Apollo 15 samples are omitted, the average is 14.4 percent. Electrostatic separation experiments in vacuum by Agosto (1985) suggest that grade and recovery percentages should be between the high 70s and the low 90s.

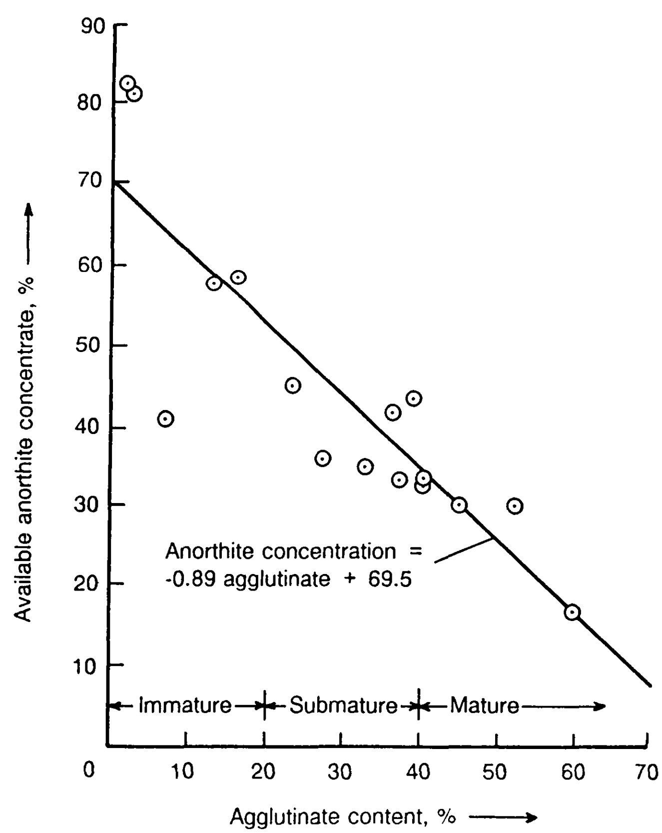


Figure 5

Relationship Between Available Anorthite and Maturity of Soil

From McKay and Williams 1979

Glasses: There are two main types of glasses found in the lunar regolith—homogeneous and heterogeneous (Taylor 1975). The homogeneous glasses are "volcanic" in origin or produced by major impacts, and the heterogeneous glasses are produced by more minor impacts. Two chemically distinct homogeneous glasses have been found to be abundant in spots: green and orange (Taylor 1975). The green glasses are of the most primitive lunar composition yet found and are a possible source of aluminum. The orange glasses are a possible source of titanium. In addition, both have surface coatings that may offer chlorine, copper, lead, zinc, and other volatile elements and compounds (Jovanovic and Reed 1973, Rhodes 1973, Chou et al. 1975, Meyer et al. 1975). However, in order to utilize this material, we would have to undertake extensive chemical processing. The heterogeneous glasses have a wide range of chemistries (Taylor 1975), and thus it would be difficult to separate them from the rest of the regolith.

Volatile species: Because the Moon has no atmosphere, the lunar regolith fines are a potential source of solar-wind-implanted ions such as H, N, C (table 10; see also, for example, Eberhardt et al. 1972 and Gibson, Bustin, and McKay 1988), and ^{3}He. Wittenberg, Santarius, and Kulcinski (1986) calculated that the Moon's surface materials contain approximately 10^9 kg of ^{3}He. If ^{3}He can be developed as an energy source, the energy payback for extracting and transporting ^{3}He to Earth is approximately 250, which is better than 10 times the payback for conventional energy sources on Earth.

TABLE 10. *Concentration of H, C, and N in Lunar Regolith Fines*
[Modified from Taylor 1975]

Site	Concentration, ppm		
	H	C	N
Apollo 11	46 - 54	142 - 226	102 - 153
Apollo 12	38 - 80	23 - 180	40 - 130
Apollo 14	36 - 70	42 - 186	80 - 164
Apollo 15	13 - 120	21 - 186	25 - 113
Apollo 16	8 - 79	31 - 280	30 - 155
Apollo 17	42 - 211	4 - 200	7 - 130
Luna 16			134 - 2100
Luna 20			80 - 800

Wittenberg, Santarius, and Kulcinski (1986) further calculated that, even if the U.S. electrical demand doubled every 25 years until the 22nd century and deuterium/helium-3 fusion provided all the electrical energy required after the year 2020, only 3 percent of the Moon's ^3He resources would be used. In addition, they concluded that "It should also be possible to use the lunar surface as a source of fuel for power plants in earth orbit, on the moon or on other planets. This lunar source of ^3He is sufficiently large to provide for a century or more of space research to exploit the extremely large ^3He reserves on Jupiter. Thus, the lunar ^3He can help deliver the 'clean' energy source that fusion scientists have been promising for over 30 years."

Fumaroles and Vapor Deposits

As I have stated previously, there is little direct evidence that fumaroles exist or ever existed on the lunar surface. The observation of gaseous emanations from the crater Alphonsus by Kozyrev (1962) and the probable fire-fountaining origin of the orange glass spheres (McKay and Heiken 1973) suggest that volcanic gases occur on the Moon. The crystallization of subsurface magma should release dissolved volatiles and, if these volatiles accumulate, then fumarolic activity should occur (Sato 1979), with possible deposition of volatile species. Another source of volatiles is emanations from the lunar interior (Gorenstein, Golub, and Bjorkholm 1974; Hodges and Hoffman 1974; Geake and Mills 1977; Middlehurst 1977; Runcorn 1977). Fumarolic-like activity may also occur through the remobilization of material from the heating associated with major meteoritic or cometary impacts (McKay et al. 1972, Jovanovic and Reed 1975, Cirlin and Housley 1980). The discovery by McKay et al. (1972) of vapor-deposited apatite, ilmenite, metallic iron, plagioclase, pyroxene, and troilite in recrystallized Apollo 14 breccias is an example of remobilization of elements by a major impact event.

The permanently dark and cold areas of the lunar polar regions may be a source of cryotrapped volatiles (Watson, Murray, and Brown 1961; Arnold 1979; Lanzerotti, Brown, and Johnson 1981). Temperatures possibly as low as 40 K suggest the possibility of both surface and subsurface ices that could survive for billions of years. However, until exploration of the polar regions occurs, we can only speculate as to the possible presence and nature of ices (Staehle 1983). If they occur in useful quantities, they will provide an overwhelming reason for locating at least some part of a base complex near a pole (Burke 1985).

Nonlunar Materials

There are two basic types of nonlunar inputs: (1) meteoritic, including cometary, and (2) solar wind. The rocks from which the lunar regolith is formed are fragmented by meteoritic and cometary impacts. This process results in the input of material of nonlunar sources (Ganapathy et al. 1970, Baedecker, Chou, and Wasson 1972; Zook 1975). The fragmented material, with its included nonlunar material, is a potential resource. For example, if large masses or concentratable fragments of chondritic materials can be located, they will be a source of volatile elements (Taylor 1975). Meteoritic debris is also a source of metallic iron, nickel, and cobalt (Dalton and Hohmann 1972; Goldstein and Axon 1973; Goldstein, Hewins, and Axon 1974; Wänke, Dreibus, and Palme 1978; Mehta and Goldstein 1980) and a potential source of the platinum group elements and gold (Ganapathy et al. 1970, Wlotzka et al. 1972, Hertogen et al. 1977).

Discussion

The surface of the Earth is dominated by water-related erosional processes, oxidation, and biological activity, whereas the surface of the Moon is dominated by bombardment processes (table 1). Internal crustal processes for both the Earth and the Moon are dominated by metamorphic reactions in which water plays an important role on Earth (figs. 3 and 4). There is no evidence of free water on the Moon. The lack of free water on the Moon significantly affects the nature of possible ore deposits on the Moon and eliminates the classes of ore deposits that are most exploitable on Earth; namely, (a) hydrothermal, which includes all base metal sulfide and precious metal vein deposits; (b) secondary mobilization and enrichment, which includes all ground-water-related ore deposits; (c) direct precipitation from a body of water, which includes evaporite deposits such as gypsum and salt; and (d) placer, which includes heavy mineral deposits such as diamond, gold, ilmenite, monazite, rutile, and zircon. These types of ore deposits have made up a significant percentage of the ores mined on Earth, because these processes concentrate the elements and the heavy minerals into exploitable deposits.

The data in tables 1 and 2 and the evaluation of figures 3 and 4 offer no evidence, direct or theoretical, for significant base metal sulfide or precious metal vein deposits on the Moon. However, we must be somewhat cautious about making categorical statements, because only nine lunar landing sites (six manned Apollo and three unmanned Luna) have been sampled and these were not chosen at random. Even though meteoritic processes result in throw-out of materials and thus a potentially wide distribution of fragmented rock types, there could be small, localized, but very concentrated sources of desirable elements or compounds that would go unrecognized in studies of particles among the returned lunar regolith fines. If concentrations of desirable elements or compounds do occur, they should be found in igneous rocks, meteoritic and cometary debris, and regolith fines that have been affected by solar wind implantation (table 2; figure 3).

In 1985 I made a pioneering effort to evaluate quantitatively the lunar regolith fines as a primary source of hydrogen. The theoretical foundation laid in that paper can be used to evaluate quantitatively any solar-wind-implanted species or any species found on or near the surface of a particle, no matter what its origin.

The known concentration range of hydrogen, nitrogen, and carbon in the lunar regolith fines is shown in table 10. Such values are often used as evidence that the Moon is devoid of water, even though 100 ppm of hydrogen is equivalent to 0.09 percent by weight of water. In addition to water, other elements necessary for the growth of plants—nitrogen and carbon (carbon dioxide)—are also present on the Moon. However, because these three elements together total less than 0.3 percent of the lunar regolith (table 10), they must be beneficiated (concentrated) before they can be economically extracted. Beneficiation of lunar regolith fines can only occur under the following conditions: (1) A relatively small portion of the fine material must contain a significant amount of the element sought. (2) That material must be separable; that is, it must have unique physical and chemical properties. (3) The separation process must be economical; that is, not labor intensive or technically complex.

In my 1985 paper I demonstrated that the lunar regolith fines meet the basic requirement for beneficiation because a major portion (a minimum of two-thirds) of the hydrogen, and probably other solar-wind-implanted elements, occurs in the less-than-20-micrometer size fraction—a relatively small part of the fines. A comparison of the lunar data of Bustin et al. (1984) with the results of my theoretical calculations (table 11) reveals excellent similarity, except for a slight but significant increase of hydrogen in the size fractions that are greater than 120 micrometers. This enrichment of the lunar samples is due to the presence of constructional particles (McKay et al. 1971, Carter 1971); namely, agglutinates (DesMarais, Hayes, and Meinschien 1974) and other types of dust-welded particles.

One aspect of the question of economics is how difficult and expensive it is to extract the solar-wind-implanted elements from the beneficiated lunar regolith fines. In 1985 I recalculated the hydrogen thermal release pattern for a sample of Apollo 11 regolith fines (10086) (Gibson and Johnson 1971) and found that approximately 81 percent of the hydrogen is released below 600°C. This calculation means that only a moderate amount of thermal energy should be required to extract a significant portion of the hydrogen, especially if advantage can be taken of daytime temperature on the lunar surface and if heat can be recycled to preheat the beneficiated fines. However, I also demonstrated that the amount of material that would have to be processed to supply 1 metric ton of hydrogen is significant, even when all efforts have been made to enhance the production. I found that, for the 63 percent of the hydrogen that occurs in the less-than-20-micrometer size fraction of Apollo 15 sample 15021 (Bustin et al. 1984), a minimum of 19 596 metric tons of lunar regolith fines would have to be processed, with 4507 metric tons of concentrate heated, yielding a recovery of 51 percent of the

TABLE 11. *Comparison of Calculated Percentages (by Volume) of Coatings (200 Å Thick) on Particles of Various Size Fractions With Measured Percentages (by Volume) of Hydrogen in Such Particles*
[From Carter 1985]

Average particle diameter, µm	Percentage of total volume of fraction that is coating	Percentage of total coating in fraction	Percentage of total hydrogen in fraction*
10.0	1.195	56.46	51.34
32.5	0.369	17.42	17.11
60.0	0.200	9.44	9.73
82.5	0.145	6.87	6.38
120.0	0.100	4.72	5.03
200.0	0.060	2.83	4.36
375.5	0.032	1.51	4.03
750.0	0.016	0.76	2.01
Total	**2.117**	**100.01**	**99.99**

*Calculated from g/g data by Bustin et al (1984) for Apollo regolith fines sample 15021 hydrogen. Although these tonnages are not high by terrestrial standards, they will probably limit production of hydrogen in the early exploitation of the lunar regolith fines to that obtained as a byproduct or coproduct from the mining and processing of other materials. The production of two or more products at the same time may be the best way to reduce costs to economical levels (Criswell 1980, Simon 1985).

It is also interesting to speculate on bringing back to Earth valuable elements, compounds, or minerals. However, the only element, compound, or mineral that by itself has economic potential for mining, processing, and return to Earth is ^3He (Wittenberg, Santarius, and Kulcinski 1986). It is very expensive to transport materials from Earth and put together an infrastructure on the lunar surface (Simon 1985). It takes at least $25 000 in 1987 dollars to deliver a pound of material to the lunar surface, which is approximately 5 times the value of a pound of gold on Earth!

In 1966, before a man walked on the Moon, Peter Flawn was insightful when he wrote,

> Because of the acceleration of change in the last half-century, this writer is not inclined to state categorically that mineral materials will never be transported through space from an extra-terrestrial source to earth. It is, however, difficult to conceive of the system under which such an enterprise could take place. Mining of local materials around extra-terrestrial bases, however, is something entirely different and makes good sense. The pioneers on earth found that where *transportation facilities* were nonexistent or where they were prohibitively expensive, they had to make do with local materials. Space pioneers will be in the same situation. Use of local minerals for sources of oxygen, for energy, and for materials will undoubtedly be more economical than large-scale transport from earth. Thus although extra-terrestrial minerals are not likely to be a source for augmenting earth supplies, they are a source which will reduce by minute amounts the export of earth minerals.

These thoughts still apply. Moreover, the comments on transportation of nonterrestrial mineral materials to Earth should remain valid at least until a significant infrastructure is in place on the lunar surface.

Conclusions

1. The type and range of lunar material resources are defined to a first approximation on the basis of analysis of samples returned, remote sensing, and theoretical considerations. Major uncertainties remain as to the presence of cryotrapped volatiles in the permanently dark and thus cold areas of the lunar polar regions and the presence of fumarolic deposits containing material rich in volatile elements or compounds.

2. Early exploitation of lunar material resources will be for shielding purposes and for local use of phases or elements that do not require extensive processing. Present knowledge suggests that this activity will be confined primarily to the minerals (plagioclase feldspars and ilmenite) and rock types that result from igneous processes, to meteoritic and cometary debris, and to regolith fines that are significantly affected by solar wind implantation.

3. Lunar regolith fines are an important source of (a) silicate minerals such as plagioclase feldspars, olivines, and pyroxenes; (b) oxide minerals such as ilmenite and spinels; (c) metallic iron-nickel-cobalt alloys; and (d) solar-wind-implanted elements such as H, N, C, and ^3He.

4. Lunar regolith fines meet the basic requirement for beneficiation because a major portion of the elements implanted by the solar wind occurs in the less-than-20-micrometer size fraction, which is a relatively small part of the lunar regolith fines.

5. Early exploitation of the lunar regolith fines for hydrogen probably will be limited to hydrogen obtained as a byproduct or coproduct from the mining and processing of other materials, because it takes at least 20 000 metric tons of typical lunar regolith fines to produce 1 metric ton of hydrogen.

6. There is no evidence, direct or theoretical, for significant base metal sulfide or precious metal vein deposits on the Moon.

7. Lack of free water on the Moon eliminates the classes of ore deposits that are most exploitable on Earth; namely, (a) hydrothermal, (b) secondary mobilization and enrichment, (c) direct precipitation from a body of water, and (d) placer.

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Ground-Based Observation of Near-Earth Asteroids

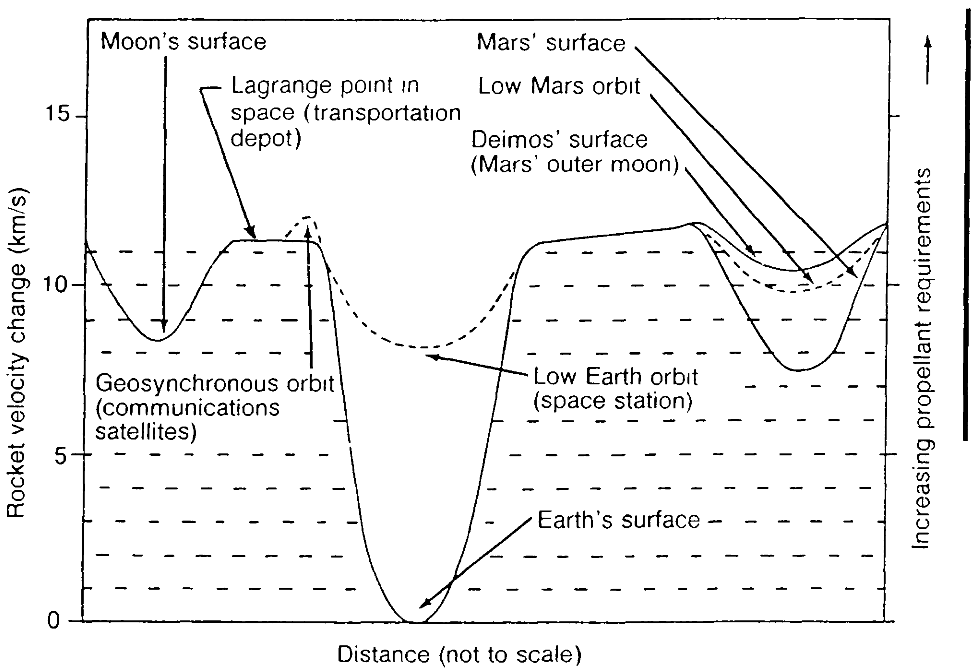
Michael J. Gaffey

An increased ground-based observation program is an essential component of any serious attempt to assess the resource potential of the near-Earth asteroids. A vigorous search and characterization program could lead to the discovery and description of about 400 to 500 near-Earth asteroids in the next 20 years. This program, in conjunction with meteorite studies, would provide the data base to ensure that the results of a small number of asteroid-rendezvous and sample-return missions could be extrapolated with confidence into a "geological base map" of the Aten, Apollo, and Amor* asteroids.

Ground-based spectral studies of nearly 30 members of the Aten/Apollo/Amor population provide good evidence that this class includes bodies composed of silicates, metal-silicates, and carbonaceous assemblages similar to those found in meteorites. It is probable that the full range of known meteoritic materials (if not an even greater diversity) is represented in the near-Earth population. These include water- and carbon-bearing C1 and C2 types and metal-silicate bodies that are 5- to 50-percent metal.

Among the relatively few known members of this large near-Earth population are objects in orbits that require less (sometimes much less) energy to reach from low Earth orbit (LEO) than the lunar surface requires. Their orbits are similar to the orbit of the Earth, though many are inclined to it. And, because they are much smaller than the Moon, they have little gravitational attraction. Thus, only a small amount of propulsive energy is required to approach or leave those whose orbits are both close and in nearly the same plane. Using current propulsion technologies, the vast majority of near-Earth asteroids are practically inaccessible. However, if there are as many near-Earth asteroids as we think there are, many more seem likely to be found that are in favorable orbits.

* The Aten asteroids are those whose orbits lie mostly within the Earth's orbit; that is, between Earth and Venus. The Apollo asteroids have orbits that cross the Earth's orbit. The Amor asteroids approach Earth on the Mars side but do not cross the Earth's orbit. These definitions were supplied by Lucy-Ann McFadden, David J. Tholen, and Glenn J. Veeder in their chapter "Physical Properties of Aten, Apollo and Amor Asteroids" in the 1989 book *Asteroids II*, ed. Richard P Binzel, Tom Gehrels, and Mildred S Matthews (Tucson. University of Arizona Press).



Velocity Changes (ΔV's) Required To Get to Various Places

Distance to objects in the inner solar system is, in many cases, not as important as the velocity that must be imparted to a spacecraft to enable it to escape the Earth's gravity, reach the object, change direction at the target object, return to Earth, and land softly. The higher the velocity required, the more rocket propellant is necessary to achieve it, and the propellant requirement increases as the square of the velocity change.

The velocity change is dominated by the velocity required to leave a planet's gravitational field. This figure illustrates the effect of "gravity wells" in the inner solar system. Getting off the Earth is the biggest effort, and most models assume that transportation in space starts from low Earth orbit. The Lagrange points and lunar orbit represent the limits of the Earth's gravity well. (Getting to geosynchronous orbit takes a little more energy than getting to lunar orbit.)

The velocity change to get from low Earth orbit to the surface of the Moon is similar to that required to reach orbit around Mars Some near-Earth asteroids require about the same velocity change as that required to get to martian orbit. The Moon and Mars have significant gravity wells of their own, however; whereas asteroids, being so small, have no significant gravity well. To return to the Earth from the lunar or martian surface requires that the velocity change be reversed.

It is the lack of a gravity well that makes asteroid missions (or missions to Mars' moons, Phobos and Deimos) attractive from an energy standpoint. To return to Earth from an asteroid or Deimos can take as little propellant as that required to go between their orbits and the edge of Earth's gravity well (the Lagrange "plateau" in the figure). From there, aerobraking can take the spacecraft to the orbit of a space station or to the surface of the Earth

Falling into the gravity well of Mars or the Earth need not take as much propellant as getting out, because the atmosphere can be used to slow down the spacecraft That was the function of the Apollo heat shield and is the function of the Space Shuttle's thermal protection tiles. Providing such an "aerobrake" to disperse the frictional energy of reentry can reduce the propellant requirement significantly

Aerobrakes are not "free," as they add mass to the spacecraft going to and returning from the target object. Improving thermal control systems and aerobrake materials will have important consequences for round-trip missions to asteroids.

Figure provided by Paul W Keaton, Los Alamos National Laboratories.

Table 12 lists the instruments that are being used or could be used to search for near-Earth asteroids. Currently, only a few near-Earth asteroids per year are being found. (See figure 6.) Table 13 lists techniques useful in characterizing asteroids and the types of information obtainable using these techniques. To be confident that usable materials could be recovered from asteroids, we need more specific characterization of their composition. A small commitment of resources (a few million dollars per year) to continue and modestly expand the efforts to find and characterize near-Earth asteroids would enable much greater progress to be made.

TABLE 12. *Near-Earth Asteroid Search Instruments*

Instrument	Detector	Status	Discovery rate per year, current full-time
Large, wide-field telescope (e.g., 48-in. or 120-cm Schmidt) [ground-based]	Photographic with daily plate survey	3-4 days/ month at 1 site	5 / 10s
Large, conventional telescope (e.g., 70-in. or 180-cm Cassegrainian) [ground-based]	CCD with real-time discrimination of fast-moving objects	Half-time operation	1 / 10s?
Infrared satellite (IRAS-type) survey [in LEO]	Liquid-helium-cooled mirror array detector for real-time detection of fast moving objects	Infrared Astronomical Satellite was flown successfully for other purposes	NA / >10s

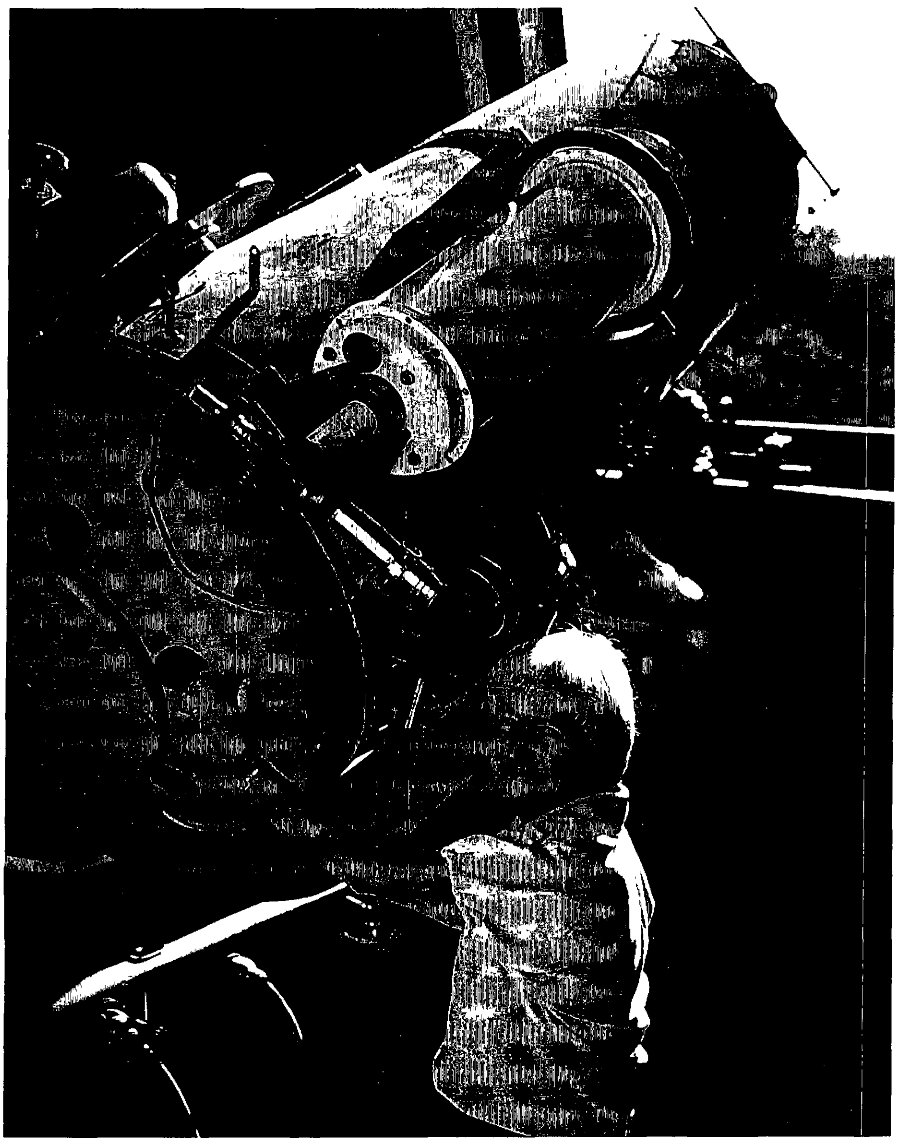


Figure 6

Schmidt Telescope

The search for asteroids is conducted with wide-field telescopes known as Schmidt telescopes. A few near-Earth asteroids are being found each year by a team including Eugene Shoemaker, Carolyn Shoemaker (shown here with the Schmidt instrument at the Palomar Observatory), and Eleanor Helin. The telescopes are scanned at the same rate as the Earth turns, so that on photographic plates the stars remain fixed points. Under these conditions, asteroids which are moving across the star field appear as streaks on the plates. The small size and scarcity of near-Earth asteroids makes their discovery a particularly tedious task.

TABLE 13. *Asteroid Characterization Techniques and Information Derived*

Technique	Information derived [Requirements and limitations]
Reflectance spectroscopy and multicolor photometry[a]	Asteroid class[1] [Not a determination of specific composition] Surface mineralogy[2] [Requires broad spectral coverage, high resolution, and high signal-to-noise ratio; knowledge of albedo improves characterization] Detection of water-bearing materials[3] [Data in the 3-μm spectral region required]
Visible photometry and lightcurve photometry[a]	Size[4] [Requires knowledge of albedo] Albedo[4] [Requires knowledge of size] Rotation period[5] [Requires a sequence of closely spaced observations over several nights] Approximate shape[6] [From analysis of lightcurves] Orientation of spin axis[6] [From variation of lightcurve form with viewing geometry]
Visible polarization[a]	Albedo[7] [Requires observations over a range of phase angles]
Infrared photometry[a]	Size[8] [Knowledge of albedo improves determination] Albedo[8] [Derived in combination with visible photometry] Relative emissivity[9] [Model-dependent indication of metal abundance or surface texture]
Radar[b]	Surface conductivity or metal abundance[10] [Model depends on assumptions of surface porosity] Diameter[10] [From duration of returned signal] Rotation rate[10] [From frequency spread and delay in signal] Shape[10] [From temporal variation of frequency spread and time delay]

TABLE 13 *(concluded)*.

Technique	Information derived [Requirements and limitations]
Passive microwave radiometry and spectroscopy[a]	Near-surface temperatures[11] Temperature gradients, conductivities, and thermal inertias
Occultations	Diameter[12] [Dependent on obtaining accurate durations from several sites] Shape[12] [Profile for moment of occultation]
Space telescope images	Moderate resolution images[13] [Approximately 30-km resolution in middle of asteroid belt]

[a] The spectral coverage and the spectral resolution of observations depend on the specific instrument and telescope being used For any particular system, the quality (signal-to-noise ratio) of the resultant data depends on the brightness of the asteroid, which is proportional to the square of its radius and the inverse square of its distance from the Earth and from the Sun At visible wavelengths the signal is also proportional to the surface albedo, and at infrared and microwave wavelengths it is proportional to 1 minus the albedo

[b]The strength of the returned radar signal is proportional to the strength of the transmitted signal, proportional to the square of the diameter of the target asteroid, and proportional to the inverse fourth power of the distance to the asteroid Asteroid distance is the major factor in data quality

The following references provide detailed reviews of the various techniques listed in this table

[1]Tholen, David J , and M Antonietta Barucci 1989 Asteroid Taxonomy In Asteroids II, ed Richard P Binzel Tom Gehrels, and Mildred Shapley Matthews, 298-315 Tucson Univ of Arizona Press

[2]Gaffey, Michael J , Jeffrey F Bell, and Dale P Cruikshank 1989 Reflectance Spectroscopy and Asteroid Surface Mineralogy In Asteroids II, 98-127

[3]Lebofsky, Larry A , Thomas D Jones, Pamela D Owensby, Michael A Feierberg, and Guy J Consolmagno 1990 The Nature of Low-Albedo Asteroids from 3-µm Multi-color Photometry Icarus **83** 16-26

[4]Bowell, Edward, and Kari Lumme 1979 Colorimetry and Magnitudes of Asteroids In Asteroids, ed Tom Gehrels, 132-169 Tucson· Univ of Arizona Press

[5]Harris, A. W , and D F Lupishko 1989 Photometric Lightcurve Observations and Reduction Techniques In Asteroids II, 39-53

[6]Magnusson, Per, et al. 1989 Determination of Pole Orientations and Shapes of Asteroids In Asteroids II, 66-97

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[8]Lebofsky, Larry A , and John R Spencer 1989 Radiometry and Thermal Modeling of Asteroids In Asteroids II, 128-147

[9]Gaffey, M J. 1989 Asteroid Surface Metal Abundances Bull American Astron Soc. **21** 963

[10]Ostro, Steven J 1989 Radar Observations of Asteroids. In Asteroids II, 192-212

[11]Webster, William J , Jr , and Kenneth J Johnston 1989 Passive Microwave Observations of Asteroids In Asteroids II, 213-227

[12]Millis, R L , and D W Dunham 1989 Precise Measurement of Asteroid Sizes and Shapes from Occultations In Asteroids II, 148-170

[13]Zellner, B , Eddie N Wells, Clark R Chapman, and D P Cruikshank 1989 Asteroid Observations with the Hubble Space Telescope and the Space Infrared Telescope Facility In Asteroids II, 949-969

A coordinated effort should include the following:

1. An increase in the level of effort, presently that of about 1 person per year to that of 5-10 persons per year. All available time on Schmidt telescopes with apertures 60 cm and larger would be used. Smaller telescopes would not detect enough asteroids to make efficient use of the observers' search time.

2. Construction of a 60-cm Schmidt telescope dedicated to the search for near-Earth asteroids. This facility could be built in 1 year, would cost from $200 000 to $300 000, and should allow investigators to discover 5 to 10 near-Earth asteroids per year. At this rate of discovery, the number of candidate asteroids for near-Earth rendezvous missions would be adequate within just a few years.

3. Construction of a 120-cm Schmidt telescope dedicated to the search for near-Earth asteroids. Such an instrument could photograph approximately 700 fields each year. The development of automatic scanning systems has eliminated the immense task of visually scanning these plates for trailed images. This next-generation search instrument is needed to achieve the goal of discovering 400 to 500 near-Earth asteroids in the next 20 years. The survey would allow the choice of an asteroid for detailed investigation possibly leading to mining operations. This telescope would take about

3 years to complete and cost from \$3 million to \$4 million. The search program would require the work of about 6 persons per year. Discovery rates with this facility should be from 20 to 30 near-Earth asteroids per year.

4. Assembly and monthly update of a central index of wide-field plates. This cooperative effort would allow rapid access to all images containing the asteroid, including those recorded before the asteroid was recognized, and would thus contribute to the precise determination of its orbit. This effort would require the equivalent of about 1 person's work per year.

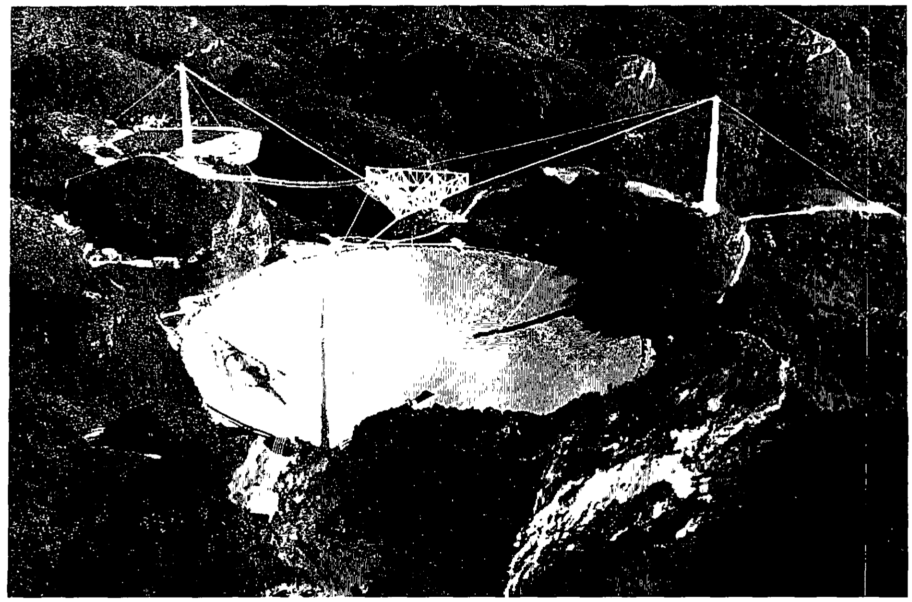
5. Application of radar to the study of near-Earth asteroids. Radar has only recently been successfully applied to asteroid studies, primarily from the Arecibo facility (see fig. 7). Because signal strength is related to the inverse fourth power of the distance to the target and because the target asteroids are relatively near, radar promises to be a very powerful technique for studying them. Radar can provide information on size, shape, and rotation rate. And radar wavelengths will be responsive to composition (e.g., metal content) and surface structure.

Without an accelerated discovery program, we will probably continue to discover only a few near-Earth asteroids each year. Only a small number of these are easily accessible to spacecraft. Therefore, in order to utilize asteroidal resources within the next 20 to 30 years, we need an expanded search program to find near-Earth asteroids and we need measurements of their physical properties to evaluate their usefulness.

Figure 7

Arecibo Observatory

The Arecibo Observatory, in Puerto Rico, is the premier radio telescope instrument used in the Earth-based study of the planets and small bodies in the solar system. It is capable of beaming a powerful signal into space and receiving the radio waves reflected from the source. The telescope has been used to map the surface characteristics of the Moon, Venus, and Mars, and recently has started to provide data on the physical properties of near-Earth asteroids. The radio wave reflection properties are affected strongly by the surface roughness and by the granularity of surface materials, and to a more limited extent by the composition of the asteroids.



Asteroid Resources*

John S. Lewis

There are three types of possible asteroidal materials that appear to be attractive for exploitation:

1. Volatiles
2. Free metals
3. Bulk dirt

Because some of the near-Earth asteroids are energetically more accessible than the Moon [require a round-trip total change in velocity (ΔV) less than 9 km/sec (though the trip time would be measured in years, not days)], such an asteroid might be chosen as the source of any useful material, even if that material was also available on the Moon. Provided that the asteroid was minable, it might therefore be chosen as the source of bulk dirt needed for shielding in low Earth orbit (LEO) or elsewhere in near-Earth space.

And the near-Earth asteroids may offer materials that are rare or absent on the surface of the Moon. Some of them are spectrally similar to ordinary and carbonaceous chondrites. These meteorites contain free metals and volatiles at a concentration about 100 times that in the lunar soil. Thus, if an asteroid was found to have one of these compositions and to be accessible and minable as well, it would be a very attractive source of such needed materials.

An asteroid of the composition of an ordinary chondrite could be processed to provide very pure iron and nickel for use in structures in LEO. The principal byproducts would be cobalt, the platinum group metals, and other useful elements such as gallium, germanium, and arsenic. These are all materials of high value and utility in an industrial economy. Some might even be valuable and useful enough to merit being returned to the surface of the Earth (though the high cost of space transportation has ruled out economical return of gold and even diamonds, thus far).

* The editor acknowledges the critical help of John Wasson, for figure 11 and its interpretation; Lucy McFadden, for the spectral classifications of the near-Earth asteroids and other clarifications; and Michael Lipschutz, for the relationship between meteorites and asteroids and other information. Wasson's figure comes from his book *Meteorites: Their Record of Early Solar-System History* (New York: W. H. Freeman and Co., 1985), p. 29. McFadden and Lipschutz are the lead authors of two chapters in the 1989 book *Asteroids II*, ed. Richard P. Binzel, Tom Gehrels, and Mildred Shapley Matthews (Tucson: Univ. of Arizona Press). McFadden's "Physical Properties of Aten, Apollo and Amor Asteroids" is coauthored by David J. Tholen and Glenn J. Veeder. Lipschutz's "Meteoritic Parent Bodies: Nature, Number, Size and Relation to Present-Day Asteroids" is coauthored by Michael J. Gaffey and Paul Pellas.

Volatiles, such as water and carbon dioxide, obviously useful in any space settlement, could be found in an asteroid that resembles a carbonaceous chondrite or one that consists of the nucleus of a former comet. Water content by weight for these materials may range from 5 percent for C2 chondrites through 10 percent in C1s to about 60 percent in typical cometary nucleus material. The abundance of organic matter in C1s is about 6 percent by weight, and nitrogen, sulfur, and chlorine are readily available. Attractive bonuses from C1s are that on the order of 10 percent of their weight may be magnetite* and about 2 percent is nickel-rich sulfides. As an alternative to returning asteroidal volatiles to LEO, the in situ extraction of water on an asteroid may be justifiable.

The Asteroid-Meteorite Relationship

Spectroscopic comparisons of asteroids with laboratory samples of meteorites show that the dominant minerals in meteorites are also the principal components of asteroid surfaces. Indeed, many asteroids have reflectance spectra that are identical with those of known classes of meteorites. See table 14. However, many asteroids appear not to belong to known classes of meteorites (although they are made of the same major minerals). Further, there is little relation between the abundance of meteorites of a given type and the abundance of asteroids of the corresponding spectral class. Of course, the large majority of the asteroids studied are in the asteroid belt, beyond the orbit of Mars, while the objects that fall on Earth must have very different orbits It is instructive to note that the commonest class of meteorites falling on Earth, the ordinary chondrites, is apparently absent in the asteroid belt, but at least one spectroscopic match for ordinary chondrites can be found among the small, poorly studied near-Earth asteroids.

We have known for many years that the Earth receives in the meteorites a biased sampling of the asteroid types as spectral reflectance classifies them. The main problem is that the most

* M. Hyman and M. W Rowe, 1983, "The Origin of Magnetite in Carbonaceous Chondrites," abstract in Lunar & Planetary Sci XIV (Houston: Lunar & Planetary Inst.), pp. 341-342.

TABLE 14. *Asteroid Types: Surface Mineralogy and Meteoritic Analogs from Reflectance Spectroscopy*[a]

Type	(No.)[b]	Inferred surface mineralogy	Possible meteoritic analogs
A	(4)	Olivine or olivine-metal	Olivine achondrites or pallasites
B C F G	(6) (88) (13) (5)	Hydrated silicates + carbon/organics/opaques	CI1-CM2 assemblages and assemblages produced by aqueous alteration and/or metamorphism of CI/CM precursor materials
D P	(26) (23)	Carbon/organic-rich silicates?	Organic-rich cosmic dust grains? CI1-CM2 plus organics?
E	(8)	Enstatite or possibly other iron-free silicates	Enstatite achondrites
M	(21)	Metal (possibly trace silicates) Metal + enstatite?	Irons (possibly with silicate inclusions) Enstatite chondrites?
Q	(1)	Olivine + pyroxene + metal	Ordinary chondrites
R	(1)	Pyroxene + olivine	Pyroxene-olivine achondrites
S	(144)	Metal +/- olivine +/- pyroxene	Pallasites with accessory pyroxene Olivine-dominated stony-irons Ureilites and primitive achondrites CV3/CO3 chondrites
V	(1)	Pyroxene +/- feldspar	Basaltic achondrites
T	(4)	Possibly similar to types P/D	

[a]Table taken from Michael J Gaffey, Jeffrey F Bell, and Dale P Cruikshank, 1989, "Reflectance Spectroscopy and Asteroid Surface Mineralogy," in *Asteroids II*, ed Richard P Binzel, Tom Gehrels, and Mildred Shapley Matthews (Tucson Univ of Arizona Press), p 114

[b]Number of asteroids classified as this type by David J Tholen in his Ph D thesis, Asteroid Taxonomy from Cluster Analysis of Photometry, Univ of Arizona, 1984

abundant meteorites (the ordinary chondrites, which comprise almost 3/4 of the meteorites we have found on Earth) have rare asteroidal analogs and the most abundant asteroids (spectral type S, which comprises about 1/3 of all the asteroids that have been classified and over 1/2 of the near-Earth asteroids that have been classified) have rare meteoritic analogs. (See figure 8 for the type distribution of the near-Earth asteroids.) The explanation for this mismatch is among the most intriguing subjects being addressed by meteoriticists and asteroid spectroscopists.

We know that asteroid discoveries are biased in favor of the brighter objects; that is, those that are large or close (in the inner as opposed to the outer belt) or have a high albedo. We know that meteorite finds are biased in favor of those that can survive atmospheric entry. There may be an accidental bias in the meteorite population: that is, they could be the products of the fragmentation of only a few, unrepresentative parent asteroids. The ordinary chondrites could come from only parts of larger asteroids. These meteorites could come from somewhere other than the asteroid belt. There may be a

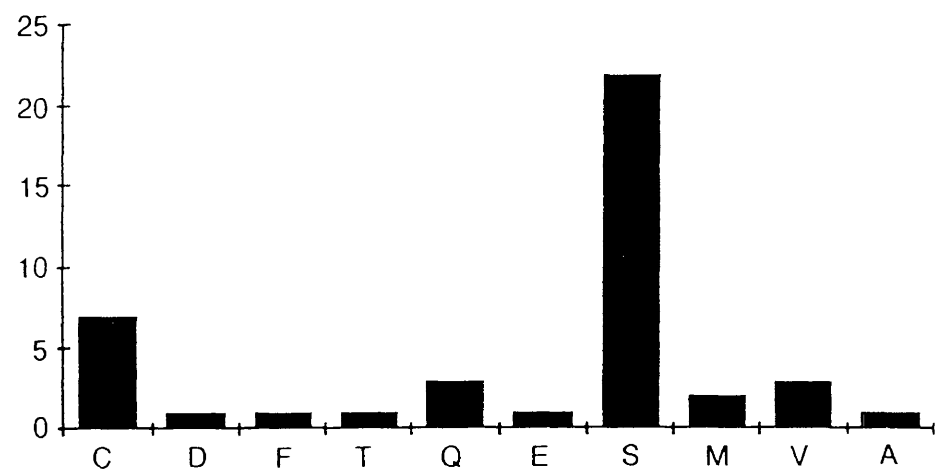


Figure 8

Spectral Type Distribution of Observed Near-Earth Asteroids

This distribution, as determined by David J. Tholen using the Eight-Color Asteroid System, has not been corrected for observational bias. The asteroid types are defined in table 14.

From Lucy-Ann McFadden, David J. Tholen, and Glenn J. Veeder, 1989, "Physical Properties of Aten, Apollo and Amor Asteroids," in Asteroids II, *ed. Richard P. Binzel, Tom Gehrels, and Mildred Shapley Matthews (Tucson: University of Arizona Press), p. 448* time bias; comparison of the well-preserved meteorites found in the Antarctic with the more weathered meteorites found elsewhere (which presumably fell within the last 200 years) suggests that Antarctica may have sampled a different meteoroid population in the past than is being sampled by contemporary, non-Antarctic falls and finds.

Thus, although we must be aware that, as Lipschutz says, "the meteorites are an incomplete and unrepresentative sample of the asteroid belt" (and of intermediate parent bodies such as the near-Earth asteroids), the volume of data on the meteorites so far exceeds the volume of data on the near-Earth asteroids that we are compelled to assume for the time being that the meteorites are adequate representations of the near-Earth asteroid population.

In this paper, I will present a brief overview of the entire range of meteorite compositions, with emphasis on the occurrence of interesting resources. I will focus on materials useful in space, especially volatiles, metals, and raw "dirt." Those few materials that may have sufficiently high market value to be worth returning to Earth will also be mentioned.

Meteorite Classes

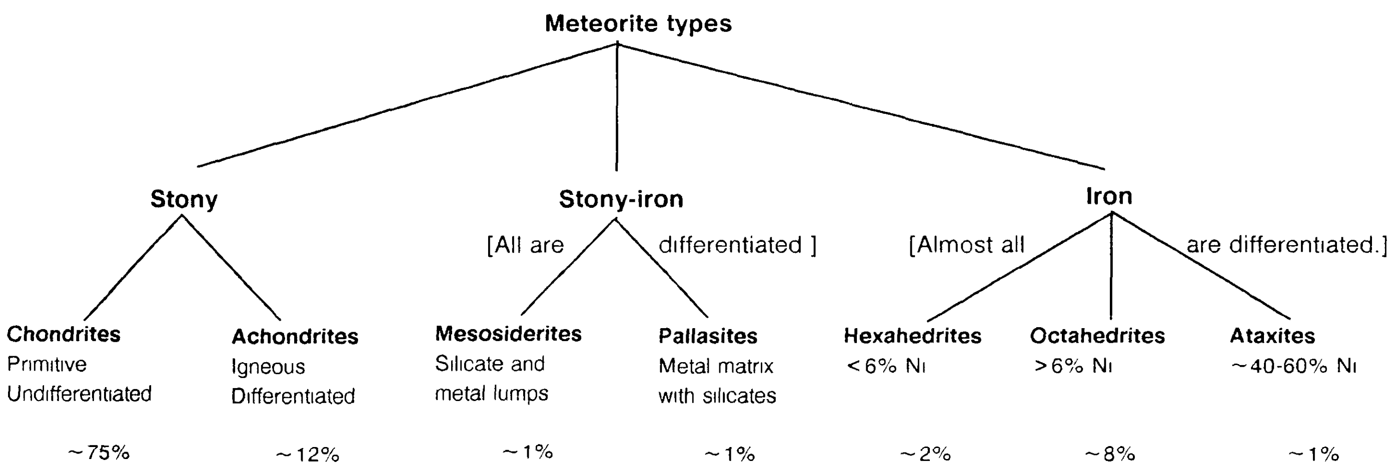
Figure 9 shows the general scheme for classification of meteorites. This scheme unifies the more than 30 known classes under the three principal headings of *stones, stony-irons*, and *irons*. Primitive solid material, in which the major rock-forming elements have about the same relative abundances as in the Sun, accounts for the subset of stony meteorites called *chondrites*. All other classes of meteorites are the results of melting and density-dependent geochemical differentiation of primitive material. Chondrites fall on Earth far more often than all these other meteorite types combined.

The prospect of mining differentiated asteroids is not encouraging. Volatiles are probably rare or absent, and free metals will probably have drained into a massive monolithic core. Conversely, chondritic asteroids, both those with high volatile content and those with high free-metal content, are attractive targets.

The various classes of chondrites differ greatly in mineralogy, oxidation state, and volatile content (fig. 10) as a consequence of having formed at different temperatures. The content (by weight) of volatile-rich, low-temperature carbonaceous (C1) chondrites is up to 20 percent water chemically bound in clay minerals, up to 6 percent organic matter, and up to 11 percent magnetite. Nitrogen is present in the organic matter, and sulfur may be found as sulfides, elemental sulfur, and water-soluble sulfates. Carbonates and halides are abundant. All members of the C1 subtype of carbonaceous chondrites are very easily crushed; so are the members of the C2 subtype. But the crushing

Figure 9

Meteorite Types *(and Presumably Types of Near-Earth Asteroids)*



strength of all other meteorite classes, including the C3 subtype, varies.* Carbonaceous chondrites make up on the order of 1 percent of all meteorite falls.

Equally rare, the enstatite (E) chondrites display markedly different compositions. All the E chondrites are in a state of extraordinary chemical reduction. Iron oxides are wholly absent and iron is found only as the sulfide troilite (FeS) and in iron-nickel-cobalt alloys. The dominant mineral is enstatite, the very pure magnesium orthosilicate. These meteorites are so strongly reduced that as much as 1 percent by weight of the metal phase in enstatite chondrites is elemental silicon in solid solution with the iron and nickel. Accessory materials such as calcium sulfide (the mineral oldhamite), magnesium sulfide (niningerite), titanium nitride (osbornite), manganese sulfide (alabandite), silicon oxynitride (sinoite), and even potassium- and titanium-bearing sulfides are found in the E chondrites or in their differentiated counterparts, the E achondrites.

However, more than 95 percent of the chondrites that fall on Earth (about 3/4 of all known meteorites) lie between the extremes represented by the E and C chondrites. These intermediate "ordinary" chondrites are subdivided into three groups according to the total amount of iron they contain and the proportion of that iron (and of the siderophilic elements) that is found as free metal: the H group with high iron content (much of it metallic), the L group with low iron content (less of it metallic), and the LL group with low iron and low free metal content. Table 15 and figure 11 show the compositional relationships among the five major classes of chondrites.

*Michael Lipschutz, personal communication with the editor

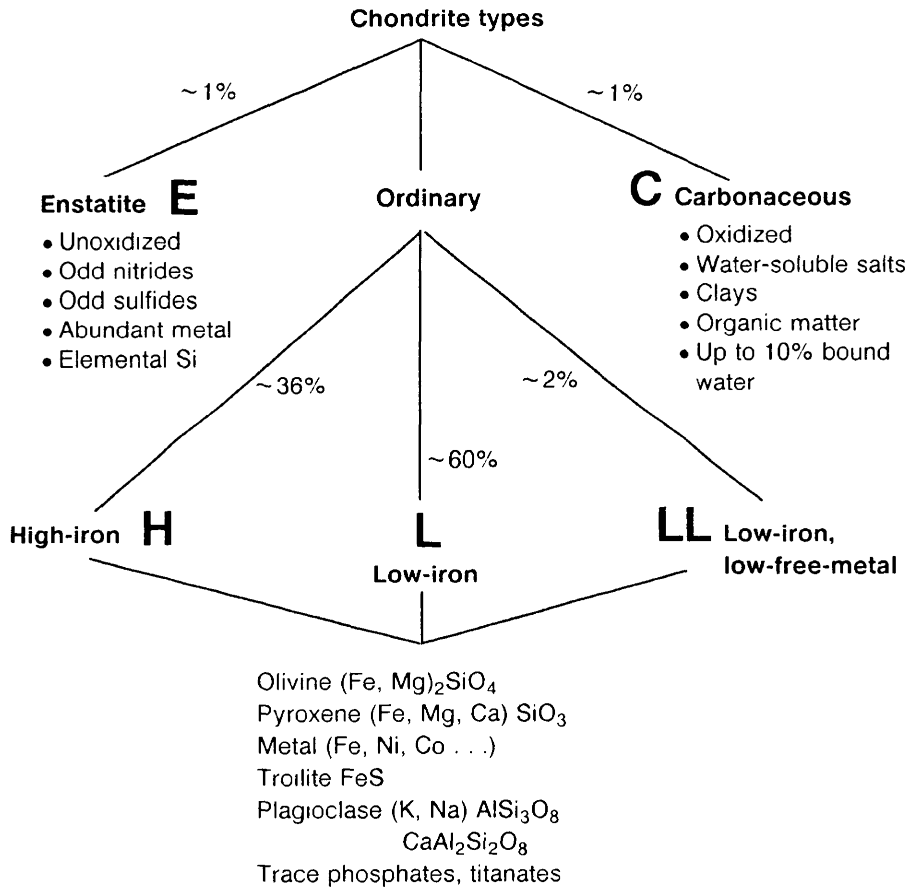


Figure 10

Classes of Chondritic Meteorites
(With Percentages of All Chondrites That Belong to Each Type)

TABLE 15. *Chemical Compositions (Weight %) of Two Enstatite Chondrites and of the Other Chondrite Groups*[a]

Class	Enstatite (E)		Ordinary		Carbonaceous (C)		
Group			H	L (& LL)[b]	C1	C2	C3
Component (wt. %)							
Si	16.47	20.48	17.08	18.67	10.40	12.96	15.58[c]
Ti	0.03	0.04	0.06	0.07	0.04	0.06	0.09
Al	0.77	1.06	1.22	1.27	0.84	1.17	1.43
Cr	0.24	0.23	0.29	0.31	0.23	0.29	0.35
Fe	33.15	22.17	27.81	21.64	18.67	21.56	24.92
Mn	0 19	0.12	0.26	0.27	0.17	0.16	0.16
Mg	10.40	13.84	14.10	15.01	9.60	11.72	14.29
Ca	1.19	0.96	1.26	1.36	1.01	1.32	1.57
Na	0.75	0 67	0.64	0 70	0.55	0.42	0.41
K	0 09	0 05	0.08	0.09	0.05	0.06	0.06
P	0 30	0.15	0 15	0.15	0.14	0.13	0 12
Ni	1.83	1.29	1.64	1.10	1.03	1.25	1.36
Co	0 08	0 09	0.09	0.06	0.05	0.06	0.08
S	5 78	3.19	1.91	2.19	5.92	3.38	2.09
H	0.13	trace	trace	trace	2.08	1.42	0.26
C	0.43	0.84	trace	trace	3.61	2.30	0.76
Fe^0/Fe_{tot}	0 70	0 75	0.60	0.29	0.00	0.00	0.10
Samples	1	1	36	68	3	10	12

The Fe entry in this table includes iron in metal, silicate, oxide, and sulfide phases.
The amount of metallic iron can be determined from that number and the ratio Fe^0/Fe_{tot}.
The amount of oxygen is not shown but is the remainder to make up 100 percent.

[a]Table modified from Robert T Dodd, 1981, *Meteorites. A Petrological-Chemical Synthesis* (Cambridge University Press), p 19

[b]Dodd grouped the low-iron (L) and low-iron, low-metal (LL) chondrites in his analysis

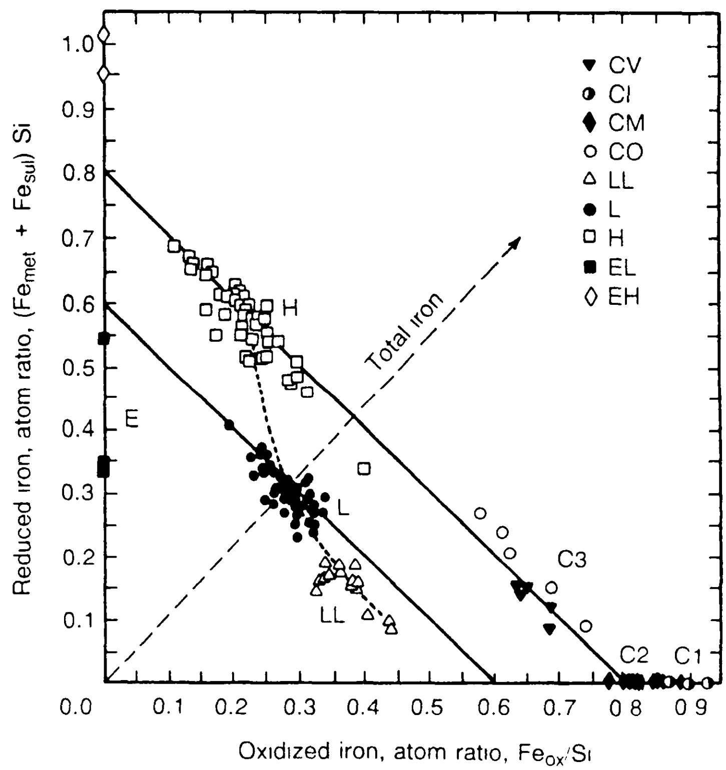
[c]Weighted average for Dodd's five CO chondrites and seven CV chondrites

Figure 11

Reduced vs. Oxidized Iron in the Five Classes of Chondritic Meteorites

Reduced iron (metallic iron and that present as FeS) in chondritic meteorites is plotted against oxidized iron (that present in silicates and, in CM and CI, as Fe_3O_4). Lines having slopes of -1 correspond to constant total Fe/Si ratios; two are shown for reference purposes. The highly reduced enstatite (EH and EL) chondrites plot along the left axis; the highly oxidized CM (C2) and CI (C1) chondrites, along the bottom axis.

Modified from John T. Wasson, 1985, Meteorites: Their Record of Early Solar-System History *(New York: W. H. Freeman and Co.), p. 29.*



The most highly oxidized ordinary chondrites (LL) and the most volatile-poor and unoxidized of the carbonaceous chondrites (C3) contain by weight only 16 percent free metal. But, because the less abundant components of the metal (nickel, cobalt, and the platinum group metals) are harder to oxidize than iron, they have been concentrated in the metal grains. Thus, the metal grains in these more oxidized chondrites contain far greater concentrations of these metals than do the metal grains in, say, the E chondrites. Nickel ranges from about 6 percent of the metal in E chondrites to 60 percent in the C3 chondrites, and cobalt and the platinum group follow suit. In each class of chondrites, the concentration of the more valuable elements in the metal phase is highest in the smallest grains.

Table 16 shows the concentrations of a number of elements in the magnetically separable (metallic) component of chondritic meteorites. It can be seen that the fourfold overall depletion of the metallic elements in the LL chondrites relative to H chondrites is accompanied by only a twofold depletion in their platinum group content. It is thus not terribly important which class of ordinary chondrites is exploited for these elements. Magnetic extraction of iron-rich phases (magnetite, FeS, etc.) might be applied to a C1 chondrite, which is lacking in free metal, since C1 chondrites contain by weight up to 11 percent magnetite and about 2 percent nickel-rich sulfides. However, it has not yet been shown that such a separation process is practical.

TABLE 16. *Concentrations of Components of the Metal Phases of Ordinary Chondrites*

	Class		
	LL	L	H
Concentration (% by wt) of total metal in meteorite.	4 (±1)	9 (±2)	16 (±3)
Nickel conc (% by wt.) in metal	25 (±5)	15 (±3)	10 (±2)
Cobalt conc. (% by wt.) in metal	1.2 (±0 2)	0.7 (±0.1)	0 5 (±0 1)
Concentration (ppm) in metal			
Platinum group metals			
Platinum	21 (±5)	13 (±1)	11 (±2)
Ruthenium	12 (±1)	8 (±1)	5.7 (±0.6)
Osmium	10 (±2)	6 (±1)	4 7 (±0.4)
Iridium	10 (±2)	5 (±1)	4.8 (±1 2)
Rhodium	1.0 (±0.2)	0.6 (±0.1)	0 5 (±0.1)
Other elements of interest			
Gallium	1 to 15	6 to 30	?
Germanium	200 (±30)	110 (±30)	?
Arsenic	1.2 (±0.2)	1.7 (±0.2)	2.1 (0 2)

Meteorites as Sources of Volatiles and Metals

If the resources of primary interest are volatiles, then, among meteorites, the carbonaceous chondrites are the target of choice. The concentrations of hydrogen, carbon, nitrogen, and sulfur in C1 chondrites are more than 100 times those in the lunar regolith: the C1s contain (by weight) 4 to 6 percent carbon, about 0.3 percent nitrogen, 6 percent sulfur, and 10 to 20 percent water (1 to 2 percent hydrogen). Most of the carbon, nitrogen, and sulfur is, like the hydrogen, compounded, though there may be some pure carbon.

If metals are the principal resource desired, then all classes of chondritic meteorites are of great interest. The abundance of free iron in a typical chondrite is much higher than on the lunar surface, where only meteoritic fragments can be found. And the amount of metallic nickel in a typical chondrite is about 100 times the nickel content of lunar regolith. As figure 11 shows, there is real variation in the Fe_{total}:Si atomic ratio [from about 0.4 in LL and some E chondrites (the EL subtype, including Indarch) to about 1.0 in C1 and some other E chondrites (the EH subtype, including Khairpur)], but the large majority of the chondrites landing on Earth (the L and H groups) have Fe_{total}:Si atomic ratios of 0.6-0.8. As shown in figure 11, the C3 chondrites and C2 chondrites contain fully as much total iron (relative to silicon) as the H chondrites; the amount of free metal in the chondrite, however, varies from about 1 percent in the C3s to about 20 percent in the H group.

Figure 12 shows the total concentrations of water and free metal in the major classes of chondrites.

Mechanical Properties of Meteorites

Meteorites have seldom been subjected to tests of bulk physical properties. There is a great variation in crushing strength and porosity, with C1 chondrites apparently most porous (more than 10 percent of their volume is pores) and weakest (crushing strengths of only a few bars). The ordinary chondrites have measured strengths ranging from 60 to 2600 bars (1 bar = 10^5 N/m^2). Iron meteorites range in strength up to 3600 bars at room temperature. At low temperature and in the presence of hydrogen, these are subject to embrittlement and should be much easier to crush. However, iron asteroids, if found, would present significant processing challenges.

Meteorites are the subset of nonterrestrial projectiles that survive entry into the atmosphere. Thus, they have been selected for strength. Stony fireballs often break up at high altitudes and yield no meteorites. Typical strengths for such fireballs are about 40 bars. The famous Tunguska object

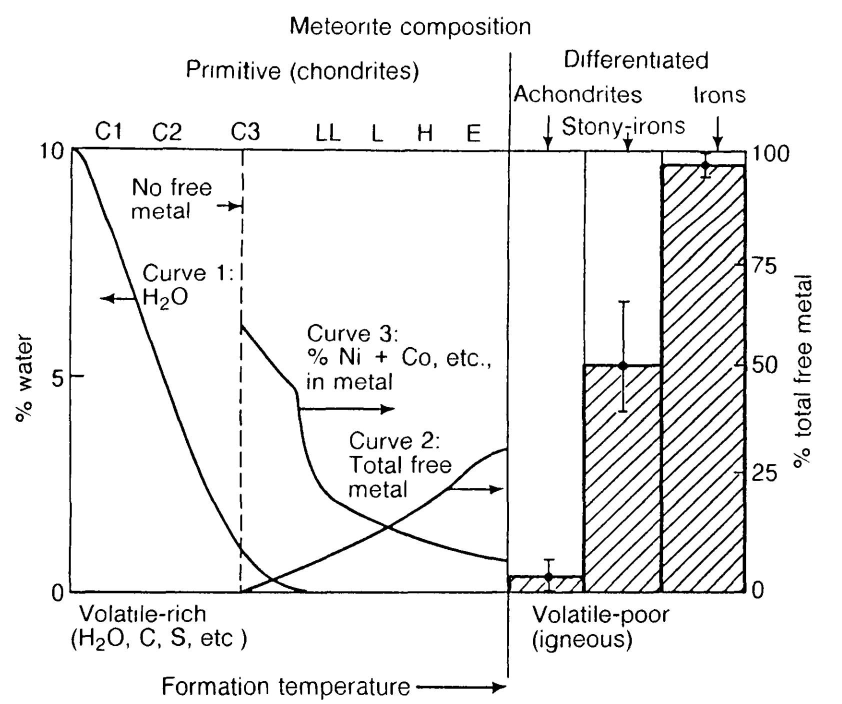


Figure 12

Volatile and Metal Variations in Meteorites

Curve 1, as measured on the left scale, shows the concentration of water in different types of chondritic meteorites. The carbonaceous chondrites contain the most water and become progressively less hydrous in going from type C1 to type C3 The ordinary chondrites (LL, L, and H) contain even less water. Most of the other common volatile species (carbon as CO_2, sulfur, etc) are also present in significant amounts only in the meteorites that contain significant water.

Curve 2, as measured on the right scale, shows the total free metal in these same meteorite types. The total free metal (that is, the metallic elements that are not combined as oxides, silicates, etc) generally increases as water decreases. As curve 3 (measured on the right scale) shows, the concentration of nickel, cobalt, and the platinum group elements within the metal phase is generally highest in meteorites having the lowest amounts of free metal.

The amount of free metal in differentiated meteorites is shown by the shaded areas as measured on the right scale that detonated over Siberia in 1908 completely ruptured under an aerodynamic pressure estimated at 200 bars. Fireballs associated with the orbits of known comets break up at loadings of 0.1 to 1 bar. This may be a very important and relevant datum, since some near-Earth asteroids are thought to be extinct comet nuclei. Beneath surface dust mantles, such asteroids may be 60 percent or more ice.

The available data on the crushing strengths of Earth-crossing bodies are summarized in table 17.

TABLE 17. *Crushing Strengths of Lunar Materials and Various Types of Meteors*

		Crushing strength, bars (1 bar = 10^5 N/m^2)
Moon		
	Regolith—precrushed	0
	Rocks (anorthosite, basalt)	~2500
Meteors		
	Irons —room temperature	3600
	—low temperature (Brecher)	< 1000
	Stones—measured (L)	>60 <2600
	Fireballs that yield stones (Lost City, Innisfree)	>200
	Tunguska explosion	200
	Fireballs	
	PN40503	30
	EN160166	50
	Cometary fireballs	>0.1 <1

Asteroid Orbits

Eleanor Helin has recently summarized for the Spacewatch Report the orbital data on the asteroids crossing the Earth's orbit and closely approaching the Earth. An updated version of this list (through 1984)* is given in table 18. The orbital eccentricities of these asteroids range from 0.182 to 0.894, with an average (and most probable) value of 0.55. Inclinations range from a low of 1.4 degrees for 1982 DB up to over 68 degrees. Those asteroids which take the least energy to reach from Earth must have low inclinations *(i)* and eccentricities *(e)* and should have semimajor axes not too different from Earth's. Asteroids with orbital periods greater than 1 year are usually easiest to reach if their perihelion distance is near 1 astronomical unit (AU), the mean Earth-Sun distance. A simple but useful approximation rule is that an asteroid will be accessible with a round-trip total change in velocity (ΔV) of less than 6 km/sec if $20e + i$ is less than 14 and the perihelion distance is between 0.8 and 1.15 AU. The first criterion is met by 8 of the 63 known near-Earth asteroids, and 7 satisfy both criteria. Of these, five have round-trip ΔV's under 6 km/sec, and two are just over the limit. For comparison, the ΔV for ascent from low Earth orbit (LEO) to the lunar surface is 6 km/sec one-way and 9 km/sec round-trip. The most favorable asteroid, 1982 DB, requires less than 4.6 km/sec for a round trip.†

*A further updated list (through 1988) is available in the chapter by McFadden, Tholen, and Veeder in *Asteroids II*.

† It should be noted, however, that we do not have a spectral type for 1982 DB. Two (1982 XB and 1943 Anteros) of the other four asteroids listed in table 19 have been classified (as S). Only one other (3908 1980 PA) of the asteroids meeting these criteria for accessibility has been classified (as V).

TABLE 18. *Near-Earth Asteroids—Atens, Apollos, and Amors*
[After Eleanor Helin in Spacewatch Report]

Name/number[a]	Discovery year	Perihelion distance	Aphelion distance	Semimajor axis	Eccen-tricity	Incli-nation	Spectral type[b]
3200 Phaethon	1983	0.14	2.47	1.30	0.894	22.8	F
1566 Icarus	1949	0.19	1.97	1.08	.827	23.0	S
2212 Hephaistos	1978	0.36	3.97	2.16	.835	11.9	SG[c]
1974 MA	1974	0.42	3.13	1.78	762	37.8	
2101 Adonis	1936	0.44	3.30	1.87	.764	1.4	
2340 Hathor	1976	0.46	1 22	0.84	.450	5.9	CSU[d]
2100 Ra-Shalom	1978	0.47	1 20	0 83	.437	15.8	C
1954 XA	1954	0.51	1.05	0.78	.345	3.9	
1984 KB	1984	0.53	3.88	2 21	.760	4 6	S
3362 Khufu	1984	0.53	1.46	0.99	.469	9.9	
1982 TA	1982	0.53	4.07	2.30	.769	12.1	
1864 Daedalus	1971	0.56	2.36	1.46	.615	22.1	SQ
1865 Cerberus	1971	0.58	1.58	1 08	.467	16.1	S
Hermes (1937 UB)	1937	0.62	2.66	1 64	.624	6.2	
1981 Midas	1973	0.62	2.93	1.78	650	39.8	
2201 Oljato	1947	0.63	3.72	2 17	.712	2.5	
1981 VA	1981	0.63	4.22	2.46	744	22.0	
1862 Apollo	1932	0.65	2.29	1.47	.560	6.4	Q
1979 XB	1979	0.65	3.88	2.26	.713	24.9	
2063 Bacchus	1977	0.70	1.45	1.08	.349	9.4	
1685 Toro	1948	0.77	1.96	1 37	.436	9.4	S
1983 LC	1983	0.77	4.50	2.63	.711	1.5	
2062 Aten	1976	0.79	1.14	0 97	.182	18.9	S
2135 Aristaeus	1977	0.79	2.40	1 60	.503	23.0	
1983 VA	1983	0.81	3.67	2 24	.636	15.4	
3361 Orpheus	1982	0 82	1.60	1 21	.322	2.7	
6743 P-L	1960	0.82	2.42	1.62	.493	7 3	
1983 TF_2	1983	0.82	3.62	2 61	.387	7 8	
2329 Orthos	1976	0.82	3.99	2.40	.658	24.4	
1620 Geographos	1951	0.83	1.66	1.24	.335	13.3	S
1959 LM	1959	0 83	1.85	1.34	.379	3.3	
1950 DA	1950	0.84	2.53	1 68	.502	12.1	
1866 Sisyphus	1972	0.87	2.92	1.89	.540	41.1	
1978 CA	1978	0.88	1.37	1.12	.215	26.1	S
1973 NA	1973	0.88	4.04	2.46	.642	68.1	

TABLE 18 *(concluded)*.

Name/number	Discovery year	Perihelion distance	Aphelion distance	Semimajor axis	Eccen-tricity	Incli-nation	Spectral type
1863 Antinous	1948	0.89	3.63	2.26	0 606	18 4	SU
2102 Tantalus	1975	0.91	1.67	1.29	298	64 0	
1982 BB	1982	0.91	1.91	1.41	.355	20 9	E
6344 P-L	1960	0 94	4.21	2.58	.635	4.6	
1982 DB	1982	0.95	2.02	1.49	.360	1.4	
1979 VA	1979	0.98	4.29	2.64	.627	2 8	CF
3671 Dionysius	1984	1 01	3.41	2.21	.544	13.7	
3757 1982 XB	1982	1.01	2.70	1.86	.454	3.9	S
3122 1981 ET_3	1981	1 02	2.52	1 77	422	22 2	
2608 Seneca	1978	1.02	3.93	2.48	.587	15.6	S
3908 1980 PA	1980	1.04	2.82	1.93	.459	2 2	V
1980 AA	1980	1.05	2.73	1.89	444	4.2	
2061 Anza	1960	1.05	3.48	2.26	537	3.7	TCG
1915 Quetzalcoatl	1953	1.05	3.99	2.52	.583	20.5	S
1943 Anteros	1973	1.06	1.80	1.43	256	8.7	S
1917 Cuyo	1968	1.06	3.23	2.15	.505	24.0	
3551 1983 RD	1983	1 07	3.12	2.10	.488	9 5	V
1221 Amor	1932	1.08	2.76	1.92	.436	11 9	
1980 WF	1980	1.08	3.38	2.23	.514	6.4	QU
1981 QB	1981	1.08	3.39	2.24	.518	37.1	
1983 RB	1983	1.09	3.35	2.22	.490	18.0	
3288 Seleucus	1982	1.10	2.96	2.03	.457	5 9	S
1982 YA	1982	1.11	5.09	3.10	.641	33.2	
1627 Ivar	1929	1.12	2.60	1.86	.397	8.4	S
1580 Betulia	1950	1 12	3.27	2.20	.490	52.0	C
2202 Pele	1972	1.12	3.46	2.29	.510	8 8	
433 Eros	1898	1.13	1.78	1.46	.223	10.8	S
887 Alinda	1918	1.15	3.88	2.52	544	9.1	S

[a]When first discovered, asteroids are given a provisional designation which consists basically of the year and two letters The first letter refers to the half-month interval in which it was discovered; the second, to the chronological order of its announcement within that particular half-month interval So, for example, 1982 DB was the second (B) asteroid discovered during the second half of February (D) in 1982 After the orbit of an asteroid has been well enough determined that it can be found again, it is given a sequential number and, when its discoverer can think of one, a name Names seem to be needed for Amors 3757 1982 XB, 3122 1981 ET_3, 3908 1980 PA, and 3551 1983 RD, so readers with lovely ideas may submit them to the International Astronomical Union, Commission 20 (Positions and Motions of Minor Planets, Comets and Satellites)

[b]See table 14 for the definitions of these spectral types and possible meteoritic analogs of them

[c]When more than one spectral type is listed, the indication is that the data are ambiguous or noisy

[d]U = Unclassified

The best possible target would be a body that can be reached simply by achieving escape velocity from Earth and which is about to collide with the Earth (so that no return propulsion is required). The round trip ΔV from LEO for this unattainably ideal case is about 3.4 km/sec. A reasonable estimate of the number of near-Earth asteroids with radii of 1 km or more yet to be discovered is 1000 to 4000. Estimating that 10 percent of them will be in accessible orbits (round-trip total $\Delta V < 6$ km/sec), some 100 to 400 1-kilometer-size bodies should be available for exploitation. The number of bodies with radii of 100 m to 1 km is probably several hundred times as large.

The martian satellites Phobos and Deimos are less attractive in terms of the energy needed to reach them than the near-Earth asteroids but still more accessible for exploitation than the surface of the Moon. Like the Moon, Phobos and Deimos apparently have a regolith and lack an atmosphere. Three independent sources of information—thermal inertia measurements and photographs made from Mariner 9 and Viking and ground-based radar measurements—indicate the presence of a lunar-like regolith that is tens of meters deep in some places. Measurements of the densities of Phobos and Deimos, their albedo (dark), and their spectral reflectance are similar to those for carbonaceous chondrite meteorites and the possibly organic-rich D- and P-type asteroids. However, ground-based photometry of Deimos made during the 1988 opposition of Mars shows no 3-micron water band in its spectrum, and data from the Soviet spacecraft Phobos 2 must be thermally modeled before these images and spectra can provide information on the presence of water on Phobos. Thus, to associate the composition of Phobos and Deimos with any meteorite type would require a mission capable of taking a chemical inventory of these satellites.*

*Lucy McFadden, 1989, in vol. VI of Exploration Studies Technical Report, published by the Office of Exploration, Johnson Space Center, NASA TM-4170, pp. 2-6 & 2-7.

The ΔV requirements for the outbound (LEO to surface of body) and inbound (surface of body to LEO) legs and the trip times for asteroidal, lunar, and martian trajectories are compared in table 19. Note that the Mars system is mainly useful for supplying resources to support Mars endeavors. However, return of martian satellite materials to LEO is somewhat more attractive energetically than return of lunar materials to LEO (return ΔV's about 40% lower).

TABLE 19. *ΔV's and Trip Times Between LEO and the Surfaces of the Moon, Selected Asteroids, Mars, and Phobos/Deimos**

Body	Outbound		Inbound	
	ΔV, LEO ⟶ surface, km/sec	Time of flight, days	ΔV, surface ⟶ LEO, km/sec	Time of flight, days
Asteroids:				
1982 DB	4.45	210	0.06	480
1982 XB	5.30	220	0.22	470
1982 HR	5.30	180	0.26	320
1980 AA	5.40	690	0.36	450
1943 Anteros	5.27	390	0.39	290
Moon	6.00	3	3.10	3
Mars	4.80	270	5.70	270
Phobos/Deimos	5.60	270	1.80	270

*All returns to LEO are via aerocapture All arrivals in the Mars system are also via aerocapture in the martian atmosphere

Asteroids as Targets for Resource Exploitation

Although both meteoriticists and asteroid spectroscopists are puzzled over the lack of correspondence between types of meteorites as analyzed in the laboratory and types of asteroids as measured by remote sensing of their surface mineralogy, there are indications in these spectral reflectance data that some of the near-Earth asteroids resemble the volatile-rich carbonaceous chondrites. So useful would volatiles, including water and carbon dioxide, be in space settlements that additional support for the effort to find and characterize more of these asteroids seems warranted. (See the preceding paper by Mike Gaffey.)

Though we have no spectral typing of the most accessible asteroid, 1982 DB, the fact that a round trip to it or one of several other near-Earth asteroids requires less energy than a round trip to the surface of the Moon is another reason to keep looking for an asteroid that is both accessible and of a desirable composition. Should such a candidate for resource exploitation be found, then we would want to send a reconnaissance mission to it to determine if it is really a mining prospect. (See Rich Gertsch's subsequent paper on asteroid mining.)

Lunar Resource Evaluation and Mine Site Selection

A. Edward Bence

I have considered two scenarios in this evaluation of lunar mineral resources and the selection of possible mining and processing sites. The first scenario assumes that no new surface or near-surface data will be available before site selection (presumably one of the Apollo sites). The second scenario assumes that additional surface geology data will have been obtained by a lunar orbiter mission, an unmanned sample return mission (or missions), and followup manned missions.

Regardless of the scenario, once a potentially favorable mine site has been identified, a minimum amount of fundamental data is needed to assess the resources at that site and to evaluate its suitability for mining and downstream processing. Since much of the required data depends on the target mineral(s), information on the resource, its beneficiation, and the refining, smelting, and fabricating processes must be factored into the evaluation. The annual capacity and producing lifetime of the mine and its associated processing plant must be estimated before the resource reserves can be assessed. The available market for the product largely determines the capacity and lifetime of the mine.

While realistic market determination is several years away, this study starts by assuming a 40 000-metric-ton-per-year lunar mining operation with a minimum lifetime of 10 years. This size would be sufficient to supply 100 metric tons of liquid oxygen (LOX) per year to low Earth orbit (LEO), assuming a 100-percent extraction efficiency and using an additional 300 metric tons of lunar oxygen to deliver the usable lunar oxygen to LEO and to bring tankers and hydrogen back to the Moon.

A 10-year operation requires processing of nearly 500 000 metric tons of ore. In the cases of iron-titanium mare basalts and of aluminous material from the lunar highlands, this amount of ore is insignificant compared to the potential reserves. And there should be no problem defining adequate reserves of oxygen, iron, titanium, silica, and bulk materials at any otherwise acceptable site.

How does one go about evaluating an ore body on the Moon? On Earth it is fairly straightforward. Data on ore grade, grade continuity, geometry and size of the ore body, grain size and grain size distribution, state of aggregation, accessibility, local relief, availability of power and water, and environmental issues must be collected, analyzed, and evaluated for economic impact. In the terrestrial case, the underlying constraint is profitability. In the lunar case, the only constraint is that the cost of placing the final product in LEO be less than the cost of bringing it from Earth.

Physical and chemical characterization of a potential ore body (prospect) on Earth is accomplished by a detailed sampling program that includes extensive core drilling. Terrestrial remote sensing rarely locates actual ore bodies, only prospects which are then explored in more detail on the ground. It is unlikely that such a sampling program would be carried out at a new landing site. Most of the exploration for lunar mining prospects would probably be done by remote sensing. The proposed resolution of the lunar resource mapper will not yield as much site information as is already known about the Apollo sites. For this reason an Apollo site, if it contains the appropriate materials, would be the most suitable site for a regolith mining operation. Since water has not yet been discovered on the Moon, it is not considered here. However, if water (ice) were discovered in the polar regions, its availability alone could strongly influence site selection.

William Snow, another participant in the summer study and the author of a paper in volume 2 entitled "Electromagnetic Launch of Lunar Material," has this to say about siting the lunar mine and oxygen production plant:

To obtain lunar oxygen at the earliest possible date, the electromagnetic launcher and liquid oxygen production plant should be deployed at one of the Apollo landing sites. Doing so would eliminate the need for a geochemical orbiter to survey the entire Moon first. To send a geochemical orbiter is good science, but it is not required for siting a lunar oxygen plant. Requiring a preliminary survey would be like having Sutter discover gold in California and then requiring a complete survey of the state before gold mining could begin. We know the mineralogy and chemistry sufficiently well at six locations on the Moon and could begin today designing and constructing a lunar oxygen processing plant on the basis of the samples brought back by the Apollo missions.

California "Forty-Niners"

Soon after the news leaked out that gold had been discovered at Sutter's mill on January 24, 1848, the California gold rush began. No one waited for a government study to determine the most likely mine locations. Instead, in the following year, tens of thousands of prospectors—the "forty-niners"—streamed to California and began to look for a share of the 550 million dollars' worth of gold that was mined there in the next 10 years.

Return to an Apollo Site

Even with our current knowledge of the Apollo sites, we need additional information to assess their suitability for mining. For example, even at the best characterized site, Apollo 17 (fig. 13), small- to medium-scale (in meters) variability in composition and particle size is not sufficiently well known. Because such characteristics profoundly affect the success of a mining and ore processing venture, many more regolith cores would need to be collected before a mine was specifically located within the area where Apollo 17 landed. The coring locations would be chosen so as to define a grid over each prospect. Each block in the grid would be on the order of several meters square by 2 meters deep. Variations in grain size and mineralogy across the grid would be used to assess the suitability of a specific prospect.

Figure 13

Typical Lunar Surface View at Apollo 17

The crater in the photograph (Ballet Crater) is about 30 meters in diameter. The rock in the foreground is about 40 centimeters across. We have good information over nearly all the surface of the Apollo 17 site on the sizes of craters and rocks on a submeter scale of resolution. However, we have very little information on variation in the third dimension, depth. We have only a single 3-meter core and a few drive tubes which penetrated less than 1 meter. Since mining would likely go to a depth of at least a few meters, knowledge of the regolith properties to that depth might be a requirement for resource evaluation.

From the Apollo 17 site at Taurus Littrow, we have the largest suite of samples and we also have the onsite observations of geologist-astronaut Jack Schmitt. By designing flexibility into mining and processing equipment, we can eliminate the need for some of the data normally required.

The chief feedstock at the Apollo 17 site would be the iron- and titanium-rich mare basalts. This "ore" could be scraped from the surface and provided as bulk material; oxygen and metallic iron could be extracted from it; and ceramics could be made from it—all with relatively simple mining, beneficiation, extraction, and processing procedures. However, even the simplest resource operations present difficulties on the lunar surface and require the support of a sophisticated transportation system and the presence of human beings.

Oxygen Production

All of the major rock types we have found on the Moon offer the potential for oxygen production in large quantities. However, ilmenite-rich mare basalts, such as those at the Apollo 17 site, seem to offer the widest range of production methods, including ilmenite reduction. Adequate separation of the ilmenite from the silicates in these basalts could be a problem. Because the ilmenite-rich soils at this site derive from basalt flows, the ilmenite crystals are both fine-grained and intergrown with silicate crystals. An answer to this separation problem might be to use an oxygen production process (such as magma electrolysis or the carbothermal reduction of silicates) which does not require beneficiation (mineral concentration).

Metal Extraction

Iron seems to be the metal most easily obtained from lunar rocks. It can be obtained as a byproduct of the direct hydrogen reduction of ilmenite and possibly by other methods. Mare basalts, relatively rich in iron and titanium, provide the best large-scale source known on the lunar surface. The basalts at the Apollo 17 site are thus an adequate source of iron.

Bulk Material

While bulk material is available at virtually any lunar location, a site with a deep, relatively fine-grained regolith is preferred from the point of view of moving large amounts of material. The Apollo 17 site provides adequate access to this resource.

Other Site Considerations

Proximity to highlands: Although we anticipate that the first lunar resources used on the Moon will be obtained from mare soils, it may be that, in the long range, materials such as aluminum, lime, and certain ceramics may best be obtained from highland rocks. Thus, selection of an initial lunar mining and processing site close to lunar highlands seems prudent. This requirement would also be satisfied by the Apollo 17 site (see fig. 14).

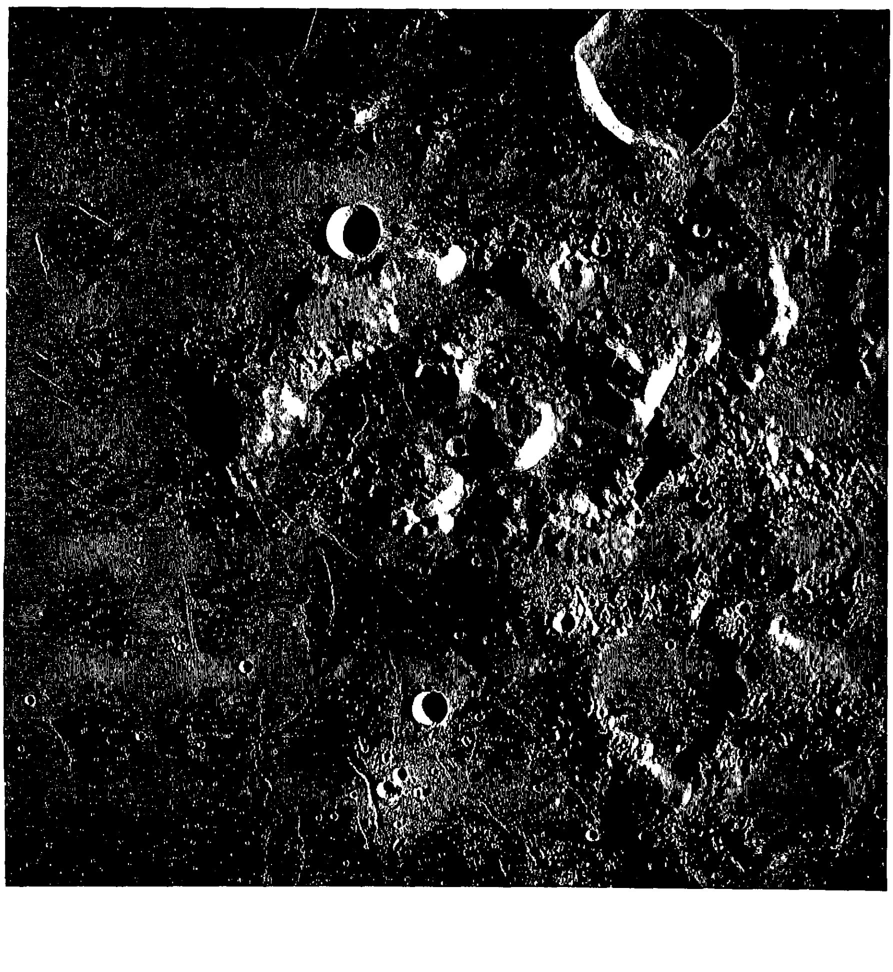


Figure 14

Orbital View of the Apollo 17 Site

Apollo 17 is an example of a site at a boundary between a mare and a highlands area In this orbital view, Mare Serenitatis can be seen to the left and part of the western highlands to the right. Between these two features, to the right of center, is the Taurus Littrow Valley (note the landslide there). Such sites have a geological diversity that, besides being scientifically interesting, may offer many different types of usable materials.

Specific siting of mine and plant: Optimum location of the first lunar mine and resource-processing plant will require additional site evaluation. Detailed characterization of the regolith is needed in order to construct an adequate ore body model. Further sampling to establish the necessary sampling grid would be a prime task for the next astronauts to occupy the Apollo 17 site. Their other chief concern will be to establish a base camp that can evolve into a permanent habitat.

New Sites

In terms of currently recognized lunar mineral resources, there is very little justification for developing a site other than an Apollo site. If, however, water were located in the polar regions, then a water-bearing site would have a higher priority than any other site. Evaluation of resources at a site or sites other than an Apollo site would require implementation of a regional exploration program. This program would include the discovery phase, presumably by an orbiter mission, in which a number of potentially favorable mining sites would be identified, each with multiple prospects. This phase would be followed by an unmanned surface mission or missions to several of the most favorable sites. Such a mission would include a Rover-type vehicle capable of obtaining regolith cores at least 2 meters deep and returning the samples to Earth. Followup manned missions would land at one or two places from which candidate mining sites are accessible.

The objectives of the earliest manned missions would be to set up an exploration base and, operating from that base, to carry out a rigorous sampling and evaluation program at a small number (no more than 5 or 6) of the most favorable prospects. From this evaluation, all the prospects found to be ore bodies would be ranked from most to least favorable on the basis of mining and milling criteria. Final site acceptance would factor in accessibility, potential hazards, power requirements, and the myriad of site details required by any mining operation.

Conclusion

Any otherwise acceptable mining site on the Moon should have adequate resources to support a 10-year, 40 000-metric-ton-per-year operation. Of the sites sampled, that of Apollo 17 is the best characterized and should require the least pre-development work. Only a site having frozen water would be more desirable. Even though the Apollo 17 site is the best characterized of the sites, pre-development work involving extensive coring of the regolith is required to assess its physical and compositional variability.

Lunar Site Characterization and Mining

Charles E. Glass

Before resources are committed to lunar mining, a significant amount of information will be needed. I hope that our workshop group will illuminate some of the more obscure areas, such as the specific requirements of an ore processing facility. Other important information can be acquired only through onsite exploration and testing.

Potential lunar mining sites can be divided into two general groups—generic sites and Apollo sites. Geologic data for both types of site are sparse and of poor spatial resolution.

Generic sites have not been visited. They are potential mine sites only because they are in lunar regions with mineralogic properties that are generally understood by comparison of remotely sensed data with data from analysis of Apollo site samples; e.g., mare sites, highland sites, or transition sites. See figure 15. Generic sites will require exploration at a variety of scales.

Initial exploration using a satellite in lunar orbit will allow regional exploration of many generic sites. Polar sites, if suitable ones can be identified, have several advantages for a mining operation. First, the continuous solar radiation at the poles would enable continuous mining operations under stable temperature and lighting conditions. (See figure 16.) Such an environment would eliminate the stress on mining equipment and personnel caused by the alternation of 2-week lunar nights and days at other sites. Second, the high thermal gradients encountered at the poles due to low Sun angles could help provide cryogenic storage for processing gases and product gases. Third, the potential occurrence of water frozen in the perpetually shadowed areas of the poles is an incentive for exploring polar sites.

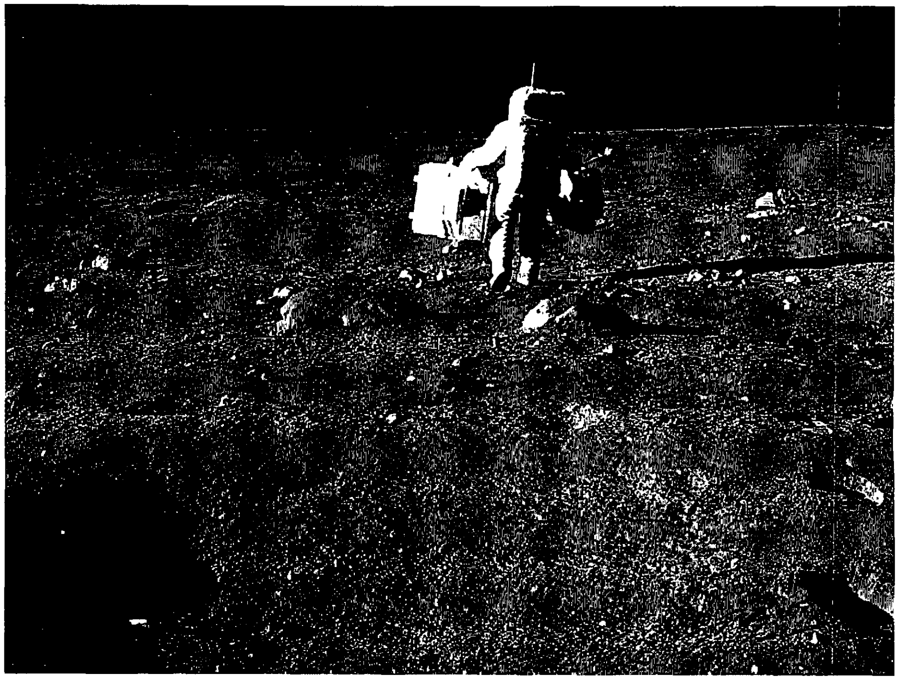
Exploration of generic sites at intermediate scales is required to bridge the gap between the low-resolution remote sensing data and the more intensive measurements made by human beings. This intermediate-scale exploration could be done by automated rovers, which should be able to cover relatively large areas rather rapidly.

The automated nature of lunar exploration will demand advances in high-resolution sensing and in computer processing and integration of data acquired by different instruments on the same roving vehicle. Knowledge gained from terrestrial mineral exploration can be used for preliminary training of automated interpretation systems, but the unique conditions of the lunar environment will likely require an intelligent computer-vision system capable of "learning" and adjusting as new data become available.

Figure 15

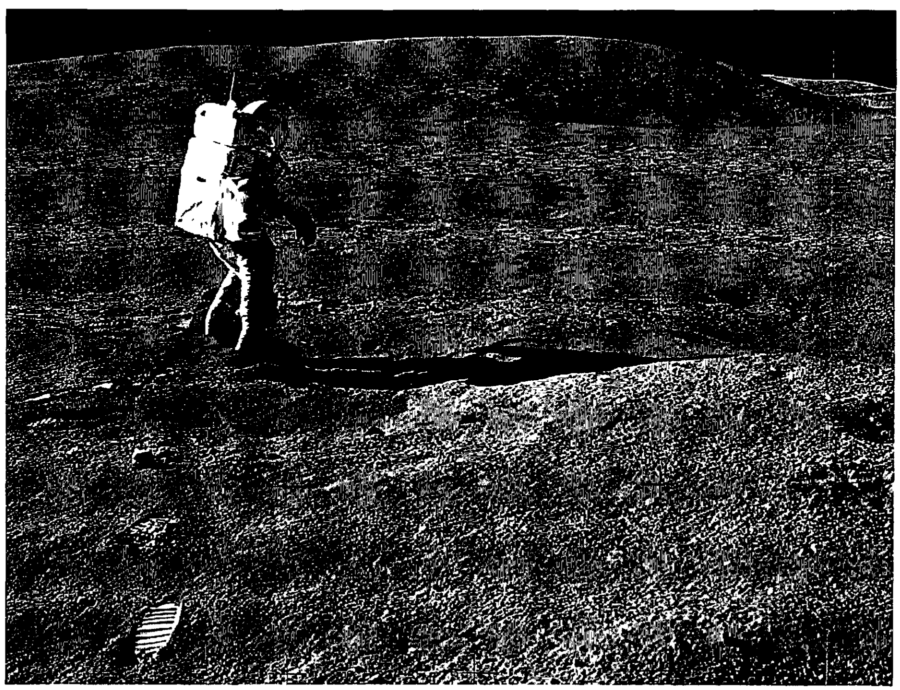
a. Mare Site

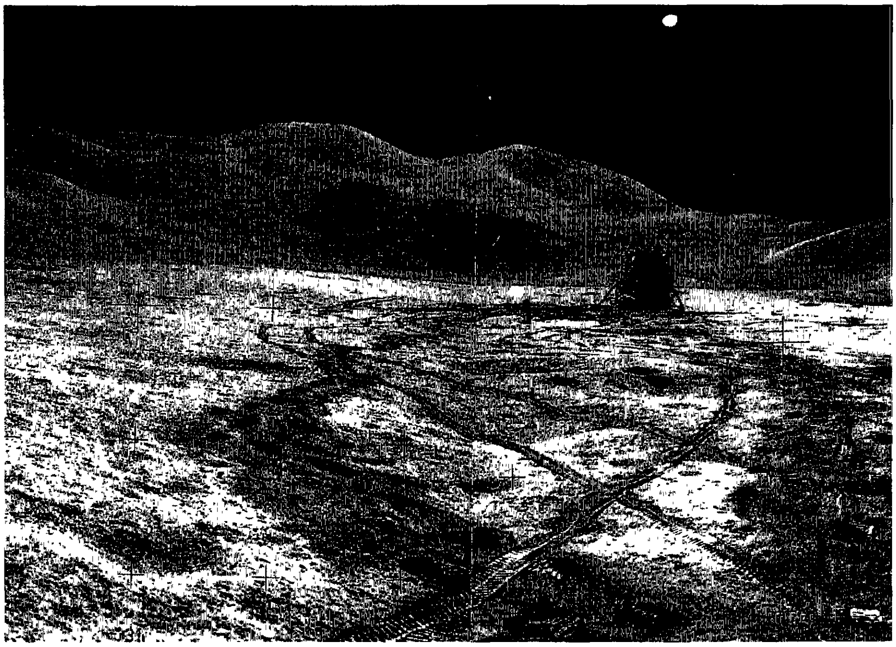
While generic sites may be like Apollo sites in overall characteristics, important details of any site cannot be predicted. Here, Buzz Aldrin is carrying a laser ranging retroreflector (LRRR) and a passive seismic experiment package (PSEP). Note the smooth, relatively flat surface. Note the deeper footprints near the rim of the small crater in the foreground. These differences in footprint depth are related to differences in local bearing strength. Local variations in bearing strength should be expected at any site and cannot be documented without onsite surveys. Consequently, site surveys may be necessary before selecting the best location for buildings, mines, landing pads, and roadways.



b. Highland Site

Here, Charlie Duke is walking across the lunar surface in the vicinity of Plum Crater at Apollo 16, a highland site. This area has far fewer small rocks on the surface than does the mare area shown in figure 15a. However, the terrain is more rolling and generally less flat. It is difficult to characterize a generic highland site. Other parts of this same Apollo 16 site are much rougher, with numerous boulders. As with the mare site, detailed site characterization would be necessary before construction of facilities could be undertaken.





c. Transition Site

Here, we see the Lunar Module at the Apollo 15 site. This site is transitional between mare and highland. It contains mare terrain in the foreground and highland terrain in the background. Generic transition sites may have features of both, including smooth flat terrain and hilly terrain. The likely complexity of such transition sites may make detailed onsite surveys even more necessary for them than for mare or highland sites.

Figure 16

Polar Solar Power System

At a base near a lunar pole, a solar reflector (the large tower in the background) directs sunlight to a heat collector, where it heats a working fluid which is used to run a turbine generator buried beneath the surface. At such a location the solar power tower can track the Sun simply by rotating around its vertical axis. Power is thus provided continuously without the 2-week nighttime period which is characteristic of nonpolar locations. This continuous power would allow continuous mining and processing operations at the pole.

Note the sharp contrasts between light and shadow in this picture. The contrasting shadows offer another advantage and might afford a third. A polar site would have a number of zones that remain in perpetual shadow, such as inside craters. These zones would be ideal locations for cryogenic storage depots; the depots would not require active cooling to maintain oxygen at liquid temperatures. And these permanently shadowed zones might have served as cold traps for collecting water released from the lunar interior or from impacts of comets or water-bearing asteroids. Such water, preserved as ice, might be minable for use in life support or processing into rocket fuel.

The triangle in the background is a mining pit. In the foreground, two scientists collect rock samples for analysis at the base.

Artist: Maralyn Vicary

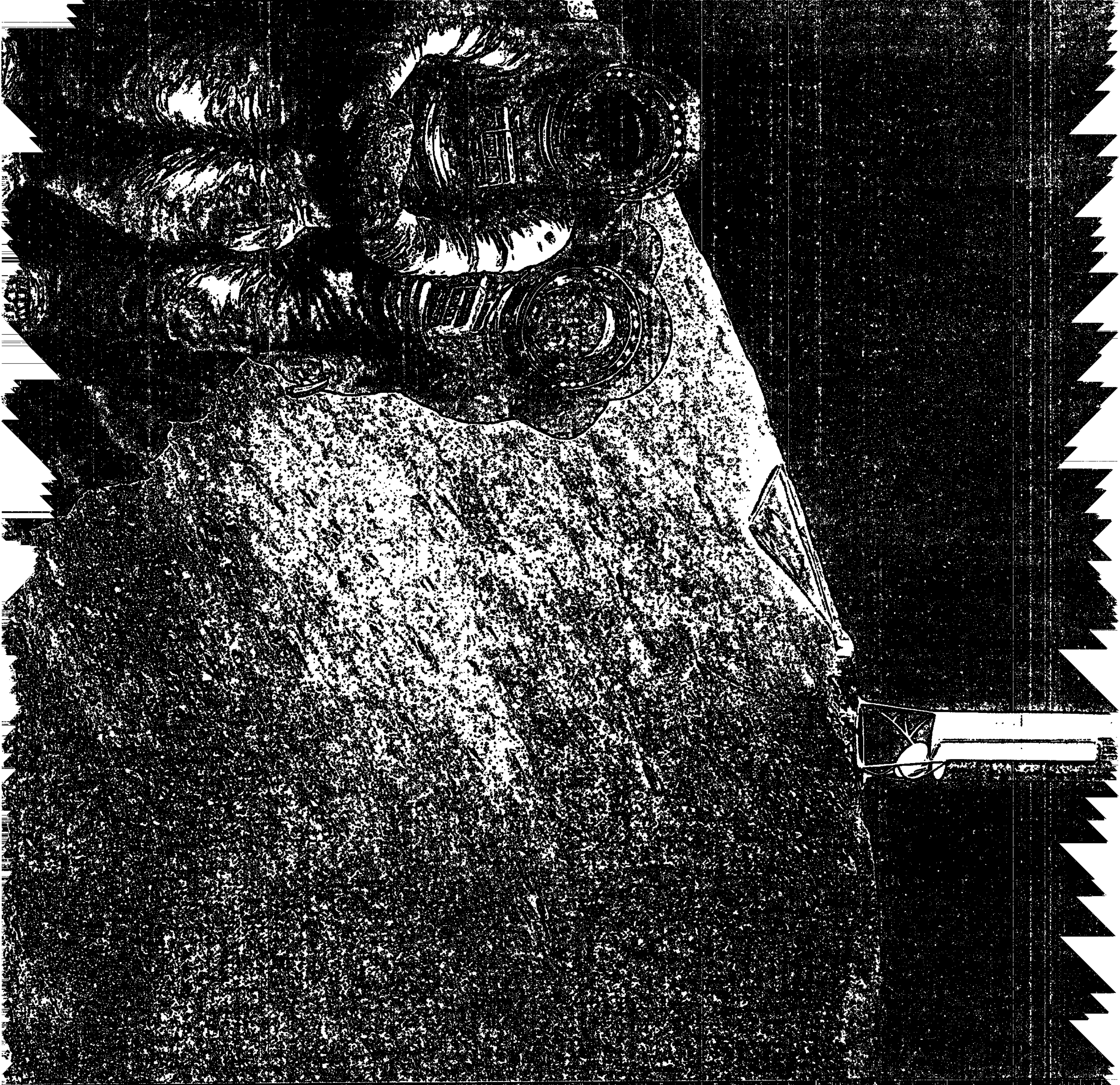
Completion of these exploration programs should bring our knowledge of generic sites up to that of the Apollo sites, the second general category. Regional exploration is not deemed necessary for the Apollo sites because of the relatively extensive body of knowledge already assembled. However, detailed site investigations to obtain specific parameters for mine design will be required for the first mining attempt.

In outlining these exploration requirements, our workshop group made several assumptions. First, we assumed that the prototype lunar mining venture should be an unqualified success. Second, we assumed that the startup product would be liquid oxygen, with the subsequent addition of such byproducts as metals for structural use, ceramics, and bulk materials for shielding. Third, we assumed that the mining operation would excavate lunar regolith and deliver a well-graded feedstock to the processing facility. (No crushing is required, with oversized material being removed mechanically.)

Specific Parameters for Mine Design

The final stage of the exploration program—to acquire specific parameters for mine design—will begin only after a chosen site has been as thoroughly explored as an Apollo site. Even for the Apollo sites, information is insufficient to assure the success of our first lunar mine. Factors that affect mining include mineralogy, grain size distribution, abrasiveness, depth of loosely compacted regolith, and surface topography. How these factors vary from place to place is not well understood. The Apollo missions were never intended to be resource appraisals. Nevertheless, a restudy of Apollo samples and survey data with an eye toward resource appraisal would be a promising first step toward obtaining the needed site detail.

Published information on Apollo 17 samples suggests a high degree of variability from place to place in mineralogy and in grain size distribution in soils. That variability is seen in samples numbering only in the tens taken over a 25-km^2



screening procedures, and plant feed simulations.

Mechanical property testing will provide parameters to assess mine stability and foundation design under both static and operational dynamic loads. It may be important, for example, to isolate the processing plant from mining and crushing vibrations either through foundation design or through physical site separation.

Measurements of the depth of the loosely compacted lunar regolith or soil will be used to design the mine, decide on the scope of the operation, and predict the volume. The depth to which one can mine without high-energy rock breakage (blasting, etc.) is important for design and planning. An unexpected change in the depth, geometry, or mineral character of the regolith could require that the mine and mill be relocated. And the fewer the equipment relocations, the lower the costs.

Surface topography will determine the general layout of the mine and processing plant. Some topographic features may be advantageous for maximizing gravity feed; others may help minimize excavation.

Requirements of the Lunar Mining System

The prototype lunar mining system should perform economically and dependably from startup to decommission. The system should meet the following requirements. However, some of these requirements may prove to be conflicting, in which case compromises and tradeoffs will have to be made.

1. It must accept and produce the volume specified.
2. The equipment should be rugged.
3. The equipment should be simple in design, simple to operate, and simple to repair.
4. The equipment should be versatile.
5. The system should be amenable to automation and later robotization.
6. Work force requirements should be low.
7. Weight and cost should be minimized.
8. The system should be testable at full scale on Earth before being put into service on the Moon.

Throughput Requirements

Because of the profit incentive, terrestrial surface mining techniques used in this country demand a significantly larger throughput than the 40 000 metric tons per year (or 10 metric tons per hour for a 4000-hour operating year) envisioned for the first lunar mine. Mining this quantity of material does not require advances in the state of the art of mining technology. Quite to the contrary, it requires scaling down the mining operation to maintain continuity in operations. For example, it may be advantageous to reduce the quantity of material excavated per unit load and increase the number of unit loads excavated per hour. The modest throughput requirements should result in increased flexibility in choosing the prototype lunar mining system.

Ruggedness of Equipment

The lunar mining equipment should be robust. It must withstand the rigors of normal mining operations, such as excavating and transporting abrasive dust, cobbles, and boulders; operating in a dusty environment; and operating continuously. In addition, it must operate in the hostile lunar environment with its severe temperature swings (except at polar sites).

Design Simplicity

The low throughput requirements encourage design simplicity, which will result in failure-resistant equipment. This design simplicity should extend to ease of repair, so as to minimize downtime. Thus, the prototype system should have few moving parts, be constrained in degrees of freedom, and be automated with exceeding care. To conserve energy, the mining and processing should take place as close together as possible.

Versatility

The unexpected is usually the most dependable occurrence in mining operations. Despite the care and thoroughness with which site characterization is performed, unexpected problems are inevitable once mining operations begin. For this reason the mining operation should be flexible and versatile enough to permit relatively easy relocation, reorientation, alteration in distribution network, and other changes during the operation cycle.

Automation

The mining system should be capable of automation to the level of sophistication of advanced automated systems at the time of implementation (see fig. 17). The system should also be flexible enough to incorporate the products of future robotics research. Full automation of routine mining operations should be incorporated within the prototype system.

The mining system should be instrumented and computer monitored to provide such operational information as power use, breakout force, and cable tension, so that stress and failure can be anticipated. In addition, mining systems having few degrees of freedom should be sought for early systems. Although laboratory automations have been demonstrated with numerous degrees of freedom and rudimentary tactile and visual sensors, it is not clear that these new advances will be sufficiently developed at the time of lunar resource exploitation.

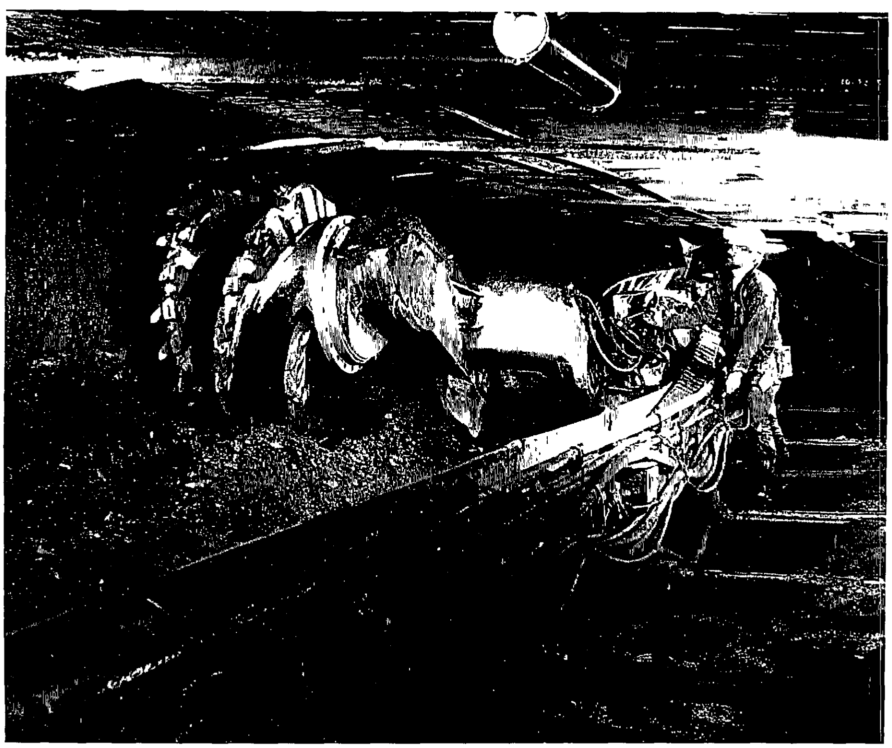


Figure 17

Coal Mine Automation

Probably the most automated mining systems in use today are in coal mines. Here in a longwall mining system is a drum shear used to fragment a large coal seam. Such systems can operate unattended for relatively long periods of time.

Photo provided by the U S Bureau of Mines and the Colorado School of Mines

Work Force Requirements

Lunar mining should be capital-intensive rather than labor-intensive. Human participation will rapidly increase cost and decrease the margin of profit. Human tending should be restricted to periodic maintenance, repair, and relocation. Routine mining operations should not require human operators.

Low Weight and Cost

It will be an asset if the mining equipment chosen for lunar resource extraction is not of the scale, in mass or dollars, common to current open-pit vehicles, such as power shovels and haulage trucks. Because of the modest soil-moving requirements, the equipment transported to the Moon need not be excessively massive or costly. There are, however, several good reasons for making excavation equipment heavy. Among these are traction, stability, and digging force. It may well be possible and desirable to design equipment so that weight can be *added* on the Moon (using lunar soil or rock, for instance). This may represent an unusual (and interesting) equipment design problem.

Equipment Testing

Rapid deployment of a lunar mining system will require that the entire system be thoroughly tested at full scale on Earth before it is launched to the Moon. All aspects of the system from software to hardware should be tested in a simulated lunar environment. Good understanding of the effects of reduced gravity and hard vacuum on the system is essential. Changes to the system during development and testing must be coordinated to ensure processing plant compatibility.

Conclusions

Lunar mining requirements do not appear to be excessively demanding in terms of volume of material processed. It seems clear, however, that the labor-intensive practices that characterize terrestrial mining will not suffice at the low-gravity, hard-vacuum, and inaccessible sites on the Moon. New research efforts are needed in three important areas. First, to develop high-speed, high-resolution through-rock vision systems that will permit more detailed and efficient mine site investigation and characterization. Second, to investigate the impact of lunar conditions on our ability to convert conventional mining and exploration equipment to lunar prototypes. Third, to develop telerobotic or fully robotic mining systems for operations on the Moon and other bodies in the inner solar system.

A Baseline Lunar Mine

Richard E. Gertsch

In this section I propose a modest lunar mining method. It illustrates the problems to be expected in lunar mining and how they might be solved. While the method is quite feasible, it is, more importantly, a useful baseline system against which to test other, possibly better, methods. Our study group proposed the slusher to stimulate discussion of how a lunar mining operation might be successfully accomplished. Critics of the slusher system are invited to propose better methods. The group noted that while nonterrestrial mining has been a vital part of past space manufacturing proposals, no one has proposed a lunar mining system in any real detail (Carrier 1979, Williams et al. 1979). The group considered it essential that the design of actual, workable, and specific lunar mining methods begin immediately.

Based on an earlier proposal (Gertsch 1983), the method is a three-drum slusher, also known as a cable-operated drag scraper (Ingersoll-Rand Company 1939, Church 1981). Its terrestrial application is quite limited, as it is relatively inefficient and inflexible. The method usually finds use in underwater mining from the shore and in moving small amounts of ore underground. It uses the same material-moving principles as more efficient, high-volume draglines.

The slusher is proposed here because the LOX-to-LEO project is a very small operation by terrestrial standards and requires a method that minimizes risk. The three-drum slusher has already proven itself in this context. It has the advantages of simplicity, ruggedness, and a very low mass to be delivered to the Moon. When lunar mining scales up, the lunarized slusher will be replaced by more efficient, high-volume methods, as has already happened here on Earth.

The Machine and Duty Cycle

Before discussing the advantages of the machine in a small-scale startup lunar mining scenario, I will describe the slusher and its duty cycle. It consists of the following modules (see figs. 18 and 19):

1. A mobile power unit and loading station—including three drums around which the cables are wound, a mechanism to place anchors, a mechanism to change tools, an optional operator cab, a dozer blade, and a conveyor to load material into the electrostatic separator
2. Three lengths of cable to operate the scraper or other mining tools
3. Two anchored pulleys
4. Interchangeable working tools, including scrapers, rakes, plows, and rippers

Figure 18

The Mobile Lunar Slusher

Several features of a mobile slusher (cable-operated drag scraper) are shown in this perspective view. The scraper loading material in the center of the pit will continue to load material until it reaches the discharge point or loading station to the left. In the method proposed in the text, the slusher will load into a mobile mill module with the aid of a conveyor. (Neither the conveyor nor the mill module is shown here. The module behind the loading station is a transporter.) The mobile power unit/loading station will be anchored (not shown) to counter the forces on it. The function of the two anchored pulleys should be clear from the illustration. The "box-type" slusher bucket has enclosed sides, which keep the very fine lunar material from spilling out while being loaded and transported

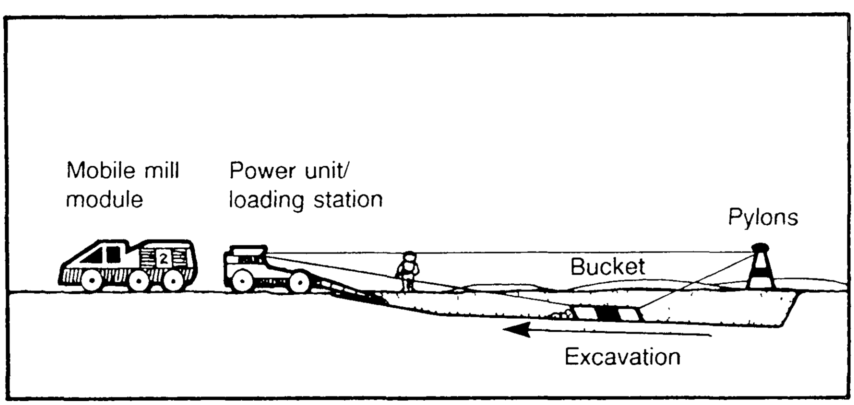


Figure 19

Side View of the Mobile Lunar Slusher

This side drawing of the slusher shows the mobile mill module behind the combination power unit and loading station. In this setup, the material from the slusher bucket is dumped directly into the mill module. The pylons holding the pulleys must be firmly anchored. They position the bucket when it is pulled out from the loading station into the mining area.

The duty cycle starts with machine setup. The mobile power/loader unit places two pulleys at appropriate locations at the mine site. They could be anchored by large augers in the firm regolith below the loose soil or by other methods. The preferred anchoring method depends on specific site characteristics. After the pulleys are anchored, the power unit similarly anchors itself. The two pulleys and the power unit form a V-shaped mining area. Because machine setup is done only infrequently, is a complex job, and requires firm anchoring, it could be left as a manual operation. For one reason, the anchoring augers might hit buried rocks before they are successfully emplaced. Further study may show that automated or teleoperated setup is also feasible and more desirable.

In this short paper, it is impossible to cover adequately all the alternatives and options, even within a well-defined system such as the slusher. However, I will mention one major alternative—a stationary power/loader unit (fig. 20), which is the terrestrial configuration. In this case, the

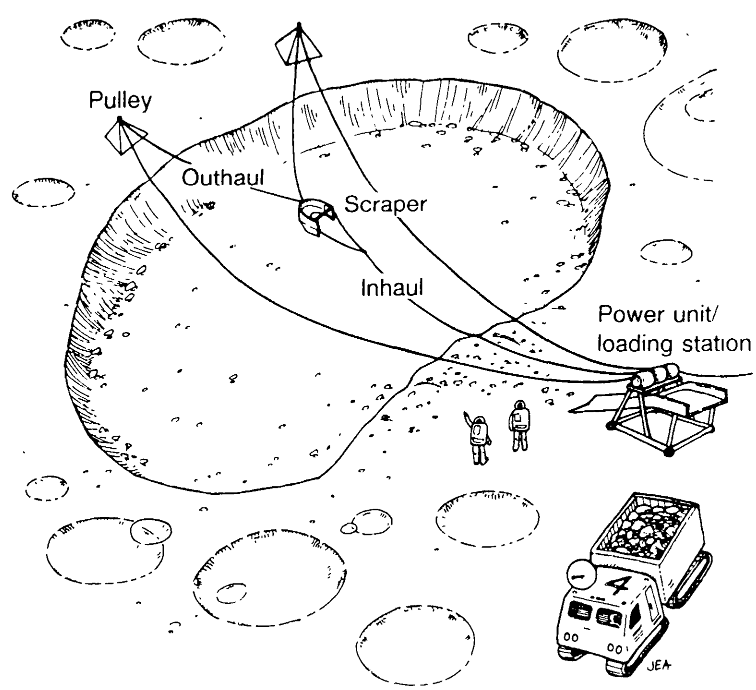


Figure 20

The Stationary Lunar Slusher

A stationary lunar slusher would have the same operational features as the mobile slusher Because it is not self-propelled, it is much simpler and lighter; however, for the same reason, it requires another vehicle to move it from site to site.

From Gertsch 1983.

slusher itself would be far simpler, but such a system would require an auxiliary vehicle to transport the slusher from site to site and set it up. A stationary slusher would be less able to remove unexpected obstacles from the pit, as I will discuss. Either way, the excavation duty cycle is basically the same.

After setup, the excavation duty cycle begins with the scraper (or other tool) at the loading station. The scraper can be moved to any point within the V by a combination of tensions on the two outhaul cables. After reaching the desired position, usually as far into the pit as possible, the scraper is pulled back to the power/loader unit by the inhaul cable. During inhaul, a combination of inhaul force and scraper weight (fig. 21) causes the scraper to fill with loose regolith and carry it back to the power/loader unit. Here the material is pulled up the ramp, discharged from the scraper onto the conveyor, and loaded directly into the mill module.

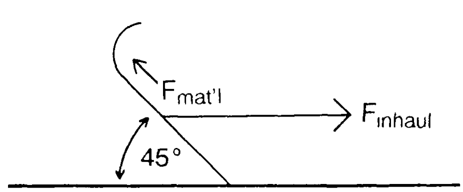


Figure 21

Forces on a Hoe Scraper

The 45-degree scraping angle is considered optimum. The angle has been determined by many years of terrestrial experience. It seems most likely that this angle will be the same for the Moon, but can we be sure? One missing force vector is the weight of the bucket. For proper operation, the weight of the bucket may need to be augmented with lunar rocks or other material.

The mill is the electrostatic separator described by Agosto in the section on beneficiation. The separator should be in direct contact with the slusher. This eliminates rehandling of the mined material, resulting in a significant energy saving, since 90 percent of the mined material will be rejected by the separator. The waste from the separator is dumped away from the production area by ballistic transport or another method. Waste transport need only be far enough to keep the separator and slusher from being buried in their own waste.

The box-like scraper will have closed sides to keep the very fine regolith from spilling out, as has been the terrestrial experience.

Because the machine defines its own mining area and machine motions are repetitive, the scraping operation is a reasonable candidate for automation. Feedback control for automatic loading of the scraper will be supplied through sensing the inhaul cable tension. Loading always requires complex motion control, but the problem is more easily resolved with a limited-motion machine such as the slusher than with fully mobile equipment, such as front-end loaders, which have unlimited freedom of motion.

After mining starts, the mobile power unit generally does not move. If an obstacle is uncovered in the pit, the mobile version of the power/loader unit can detach from its anchor and move into the pit. (The anchor is not removed from the soil unless the machine is moving to another site.) To facilitate pit work, the loading ramp is tilted up and a dozer blade extends to its working position. The blade can push boulders out of the pit or mine a small selected area. Because the power/loader unit is lightweight and consequently has poor traction characteristics, it must pull against the outhaul cables when it works a load in the pit. The complexity and uniqueness of this job argue against automating it, but automation is not impossible and teleoperation is a possibility. Both setup and power unit pit work can be done by teleoperation, except for handling severe unforeseen problems that require human intervention.

During normal operation, electric power is supplied to the power/loader unit by a stationary cable. When the power/loader unit works the pit, it gets its power through a cable reel located at the anchor. One advantage of stationary mining equipment such as the slusher (even the mobile version moves very little during excavation) is simplicity of power supply. Most mobile terrestrial equipment has diesel power, which is rugged, capable, efficient, and, most importantly, onboard. These loaders are very flexible and rugged earth-movers. The lunar alternatives are less satisfactory. Lunar loaders with onboard power would probably use electric motors driven by fuel cell or battery technology. Both are expensive options. Versions with external power must be fed electricity through a trailing cable. Terrestrial experience has shown that trailing cables are high maintenance items, but adaptation to the Moon is possible. Another possibility is a new-technology internal combustion engine, but developing the engine and finding lunar fuel sources are difficult problems.

The Lunar Environment and Machine Design Principles

The major reason for proposing the three-drum slusher is to illustrate problems to be expected in a lunar mining project.

Simplicity in Design and Operation

Compared to other mining machinery, the three-drum slusher is quite simple in design and operation. This simplicity yields several interrelated advantages.

1. Fewer moving parts, resulting in fewer failures per operating hour

2. Simpler repair, reducing downtime after a failure

3. Smaller inventory of repair parts, hence less weight to transport to the Moon

4. Simpler parts, with faster adaptability to lunar manufacture

5. Less redesign for lunar conditions, with consequently lower R&D costs

6. Fewer degrees of freedom than mobile equipment, and therefore relative ease of automation

7. Fewer project startup problems

Traction Independence

Mobile mining equipment depends on traction to generate sufficient loading forces on the blade or scraper. Most terrestrial mobile equipment loads near its traction limit. On the Moon, reduced gravity creates a less favorable inertia:traction ratio. Increases in traction are achieved by increases in mass, but increases in mass add inertia, which decreases control of a moving machine. To achieve the same traction as on the Earth, a mobile machine on the Moon would have to have six times as much mass. This greater mass would cause correspondingly higher inertial resistance to turning and slowing.

Slusher loading forces are supplied through the cable, thus almost eliminating traction problems. The scraper bucket will have to be more massive than on Earth, simply to cause the bucket to fill. To lower launch weight, the extra mass needed by the scraper bucket can be supplied by lunar rocks.

Since the slusher is a relatively low-production method, upscale lunar mining projects will eventually use mobile mining methods. It is necessary to address inertia-traction problems as early as possible. Further study may find that long-term considerations argue for using mobile equipment from the very beginning. As with the scraper bucket, the extra traction mass can be supplied by lunar materials. Perhaps traction could be improved by new tread or track designs.

Mining Flexibility and Selectivity

The lunar slusher differs from the terrestrial slusher by one major design addition: the power unit is mobile rather than stationary. This allows the machine to set itself up and eliminates the need for an auxiliary vehicle. Most important, by adding a dozer blade, the machine can doze undesirable rocks from the pit. Such large rocks would impede mining operations if the power unit were stationary.

The mobile power unit makes the machine more selective. By allowing the power/loader unit to reposition, the slusher has some ability to separate different soils during the mining process or to go into the pit and mine a small area of interest.

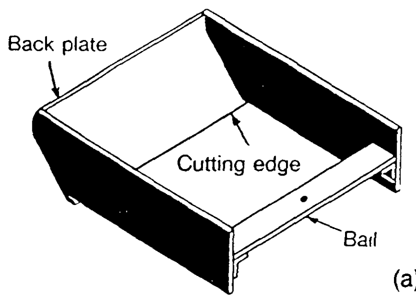
Mining Tools for Selecting Particle Size and Breaking Regolith

The ability to change from a scraper to a rake allows the machine to select different size fractions. For example, if fines are required, the area can be raked on the outhaul, so that oversized rocks are moved to the far side of the pit. Then the rake can be exchanged for a scraper to mine the remaining fines. If larger sizes are desired, they can be raked in on the inhaul.

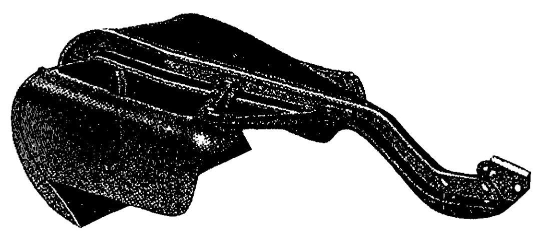
Other tools, such as rippers or plows, are used to break difficult ground. Lower levels of lunar regolith appear to have a high degree of compaction (Carrier 1972) and must be broken before mining can take place. Although it is the usual terrestrial practice, chemical explosive blasting appears to be prohibited by the high cost to transport the explosives to the Moon. The ripper or plow greatly increases machine working depth. It has already been established that the slusher, unlike mobile loading equipment, is independent of traction. This traction independence allows the slusher to break difficult ground while still maintaining a light weight. More lunar geotechnical engineering data is needed, however, and the design of the ripper is unknown. The ripper probably needs an attached weight to force it into the regolith. A plow may be better than a ripper, as its shape helps pull it into the soil, making it less gravity dependent.

High-Tech Low-Tech Mix

The redesigned slusher exemplifies a design philosophy favored by the study group. The basic machine design is nearly 100 years old and has a track record proven in many applications. See figure 22. In a lunar application, the basic operating principles remain unchanged but the machine becomes lighter, stronger, and more efficient by liberal use of advances in materials science. Light, high-strength alloys or graphite fiber might replace steel in the machine's structural and wear members. Graphite fibers might replace steel cables. Other opportunities to improve the slusher should present themselves. Thus, the lunar machine is a low-tech off-the-shelf design with high-tech execution.



(a)



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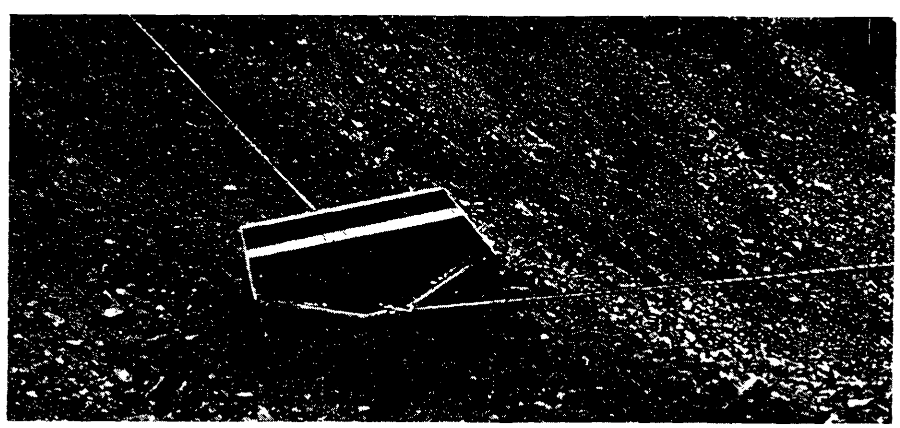


(c)

Figure 22

Box-Type Slusher Scrapers

a. Drawing of a Box-Type Scraper

b. Painting of a Full-Box Type Scraper

[Shown with a long bail and medium-length side plates.]

c. Photograph of a Box-Type Scraper

[Manufactured in the 1930s of steel plate construction in use on a stock pile.]

All three taken from Modern Methods for Scraper Mucking and Loading, *prepared, edited, and published by the Ingersoll-Rand Company in 1939.*

Two Environmental Factors

In addition to one-sixth gravity, there are two other significant lunar environmental factors worth noting: temperature extremes and electrostatic dust. Temperature extremes are easily answered by shutting down during the lunar night. Heating selected equipment components is feasible, if more expensive. Electrostatic dust is more of a problem. Machinery bearings must be protected, a problem exacerbated by the lunar vacuum, where lubricants may evaporate. One significant feature of the slusher is that it uses very few bearings, even in the mobile version. Lunar bearing designs and lubrication methods must be developed regardless of the mining method used.

Machine Specifications and Fleet Mix

The specifications and fleet mix I present are for the mobile lunar slusher. The reader should note that alternative methods, such as the stationary slusher, were included to illustrate lunar mining design problems and are not specified here. The data given below are for the proposed baseline mobile lunar three-drum system.

The needed raw material for a 100-metric-ton LOX-to-LEO project is 40 000 metric tons. The machine specified below is oversized by a factor of 2.5 or a yearly rate of 100 000 metric tons. This oversizing is to ensure the production is easily accomplished, while demonstrating that a significantly oversized machine is relatively lightweight. Even with this large oversizing, the hourly production is about 25 metric tons per hour. This rate is close to the lowest rate shown on the production table of one manufacturer (Ingersoll-Rand Form 4273A 5-G1 1971).

Specifications:

Yearly production	100 000 metric tons
Span and reach	50 meters
Mined depth	2 meters
Scraper capability	2 cubic meters
Mobile slusher weight	4.5 metric tons
Auxiliary vehicle weight	1.5 metric tons
Ballistic transporter	1 metric ton
Spare parts and tools	2 metric tons
Operation and maintenance	2 people
Foundry (optional)	5 metric tons
Total weight (without foundry):	9 metric tons

Fleet:

1 mobile slusher

1 auxiliary vehicle with small multipurpose crane

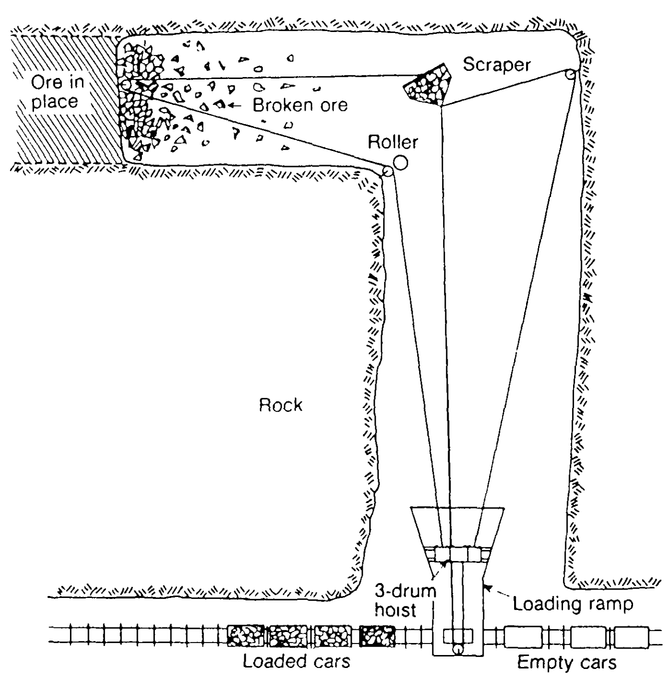
1 ballistic transporter

Lunar Mining Operations

Production Profile

The baseline self-propelled slusher excavates a triangular area 50 meters in base and height. At a mining depth of 2 meters, approximately 9000 metric tons are excavated per setup. Approximately one setup per lunar day yields a yearly raw material production of 100 000 metric tons. Mining would cease during the night, as the extremely low temperatures would make operation difficult. But milling could continue, as the mill is more easily protected from the environment. Production figures are based on terrestrial experience; lunar gravity will allow increases without increasing machine size. It should be noted that production can readily be increased by manipulating several machine variables without significantly changing machine weight. Variables such as bucket size, span, reach, and motor power all affect production. No attempt was made to optimize these factors; instead the machine was oversized to show a very basic feasibility. Empirical optimization is required during design and prototype testing.

Although the normal mining pattern is a V, mobilizing the power/loader unit allows more flexible patterns (fig. 23). The mobile unit allows the machine to excavate more convenient rectangular areas rather than triangular ones.



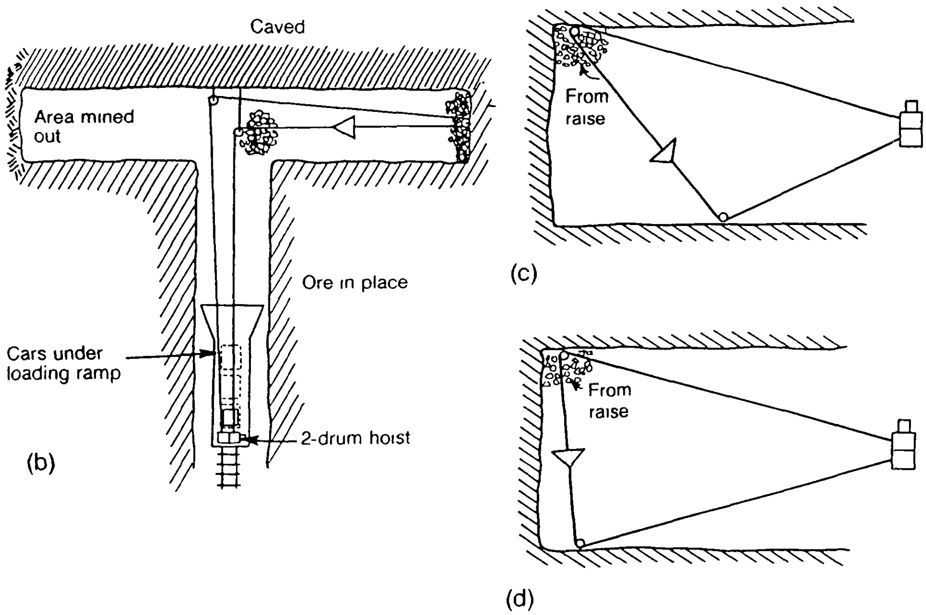
(a)

Figure 23

Various Slusher Mining Patterns

These underground slusher mining patterns demonstrate the slusher's flexibility in mining different shaped areas. Figure a shows a three-drum slusher scraping around a corner Figure b shows a two-drum slusher scraping around a corner, but note that it takes two scraping operations Figures c and d show how a changing setup allows a two-drum slusher to mine outside its restricted narrow path Both the two- and three-drum slushers can mine a wide variety of areas: triangles, rectangles, right angles, etc. However, each different setup requires downtime to reset the pulleys or the power/loader unit.

Taken from Modern Methods for Scraper Mucking and Loading *by the Ingersoll-Rand Company, 1939*



Some weight savings could be gained by using a two-drum slusher. With one outhaul cable instead of two, the machine excavates a straight line rather than a triangle. The decrease in flexibility may not be worth the small weight savings, but the two-drum solution should be investigated. By moving the power/loader unit or the pulleys, the two-drum slusher can be made to excavate a rectangular area, but the moves slow the rate.

Modular Components

Every opportunity should be taken to divide the slusher (and other equipment) into modular components. The modules should be as interchangeable and transportable as possible. Two general types of modules envisioned are large functional modules, such as mining units, material crushers, and electrostatic separators, and small equipment modules, such as electric motors and power distribution panels.

Modularity increases flexibility and reduces downtime without adding equipment weight.

1. A component needing repair can be replaced onsite with a working unit. The defective unit can then be repaired onsite or in the shirt-sleeve environment of a pressurized shop.

2. Quick component replacement allows production to continue when one component breaks. When many components break, a producing unit can frequently be assembled from the remaining units.

3. Catastrophic failure of a module, such as an electric motor, will not hamper production, as the whole unit can be replaced.

4. Increasing production simply means adding more components rather than redesigning or rebuilding the existing facilities. Upgrading one part of the operation with new designs or technology is facilitated by replacing the old components with the new.

Accomplishing modularity is relatively easy in small-production mining facilities. (By terrestrial standards, the lunar slusher operation is very small.)

Auxiliary Vehicle

A small, self-propelled auxiliary vehicle will probably be necessary, even with a mobile slusher or other mobile mining method. It will find use hauling broken components to the repair shop and replacement modules to their operating positions, as well as hauling people and materials back and forth. It should have a crane to aid in constructing habitats and repairing equipment. Adding a small conveyor to the vehicle would allow it to heap up loose regolith for habitat shielding. This general-purpose vehicle will be smaller than the vehicle required to move a stationary slusher from site to site.

Shop Facilities

A pressurized repair shop would facilitate complex repairs by providing a shirt-sleeve environment. There is no good reason to rewind an electric motor in a vacuum. Since lunar dust is ubiquitous and insidious, some system for removing dust from the shop and its equipment must be provided. Equipment from the outside must be cleaned of dust before it enters the shop.

However, a shop would add significant launch weight unless it could be fabricated on the Moon. Launch weight considerations dictate a careful mix of tools, equipment, and spare parts for the shop. The shop and repair activities are there to keep the mine operating while helping to keep transportation costs for tools and spare parts to a minimum.

In addition to tools and spare parts, the shop could eventually have a small adjacent foundry to cast pulleys, bearings, and other easily fabricated parts. The foundry will probably not be in the shop but outside in the vacuum. This plan assumes lunar metal production.

Fiberglass ropes of lunar origin to replace Earth-made cables are also candidates for early lunar manufacture, as glass is a byproduct of LOX production. Glass manufacturing methods were not considered here.

Mine Waste Disposal

Depending on required products and milling processes, some fraction of the mined material will be waste which must be removed from the production area. This fraction can be quite significant (e.g., terrestrial copper operations yield only 10 kg of product per metric ton of ore; thus, 1990 kg of that tonne is waste). The LOX-to-LEO project will generate two types of waste. Fines waste is the soil fraction rejected by electrostatic separation. Slag waste results from the smelting process. Production of liquid oxygen from regolith that is 10 percent ilmenite will generate mostly fines waste, on the order of 90 percent of the material mined or 36 000 metric tons per year. Providing a vehicle for waste disposal would add significant launch weight, and the waste disposal options must be studied.

Robert Waldron and David Carrier* have both proposed a ballistic transport mechanism that could be usable in lunar mining. It is well suited to removing fines waste. Using a simple mechanism such as an Archimedean screw (see box) or conveyor flights, it is possible to ballistically transport fines waste several hundred meters away from the production area. Their preliminary calculations indicate that the mechanism could be built at a reasonable weight. A ballistic transporter, along with a storage and feed bin, could be added as part of the mill module or as a separate module. The ballistic transporter could also be used to heap up material for habitat shielding.

*Personal communications.

The following is one of a series of 5-minute radio programs. Entitled The Engines of Our Ingenuity, *the series is written by mechanical engineer John H. Lienhard and presented by the University of Houston's College of Engineering.*

Ceredi's Pump

Now and then I run into a student who says, "I like engineering just fine; but why should I hafta take philosophy?" *He fails to see that what we* do *is shaped by the way we think about things—that our technology and our philosophy bend to fit each other. Here's an example:*

Archimedes invented a really clever pump in the third century B.C. It's been used all over the world, ever since. It looks like a tube coiled around a long axle. You tilt the axle and put its lower end in water. Then you turn it. The open end of the tube picks up water and, as the coil turns, water passes from one loop to the next until it comes out at the upper end.

It's a pretty subtle gadget—not the sort of thing you just stumble across. Archimedean pumps were widespread in the classical world, and Roman authors described them. . . Well, they tried to. We've just seen that they aren't easy to describe.

Archimedes' pump didn't do so well during the High Middle Ages when European attitudes were strongly shaped by Aristotle's philosophy. Aristotle very clearly separated motion into two kinds—motion in a straight line and rotary motion. These pumps mixed the motions. They used rotation to move water upward along an axis. They were anti-Aristotelian, and they were hard to find during the Renaissance.

(continued)

Water Screw as Illustrated in Daniel Barbaro's Vitruvius (1567)

It is difficult to understand how this water screw might have worked. But this illustration from Daniel Barbaro's commentary on Vitruvius' Ten Books on Architecture *shows that the device was known from classical times. Giuseppe Ceredi patented Archimedes' device in 1565, publishing his description of it the same year that Barbaro's book was printed.*

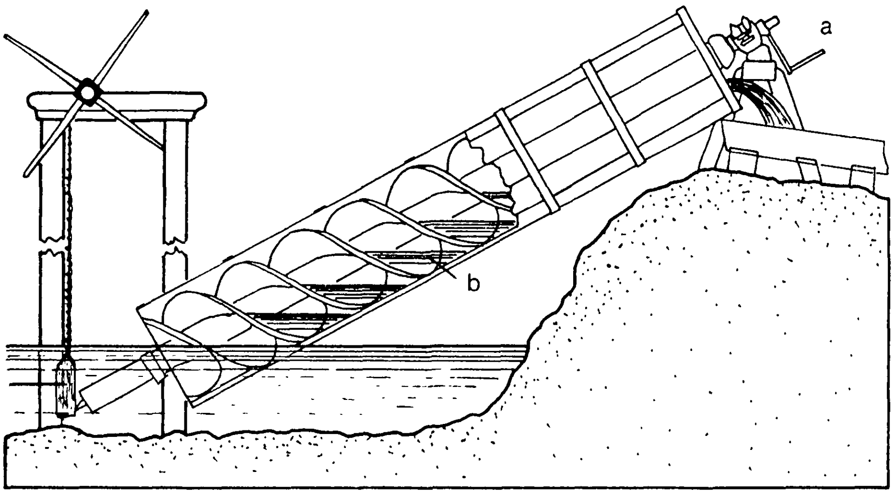
Taken from Stillman Drake, 1976, "An Agricultural Economist of the Late Renaissance," On Pre-Modern Technology and Science, *ed. Bert S. Hall and Delno C. West (Malibu, CA. Undena Publications), p. 70.*

Ballistic transport of the glassy slag waste from the smelting of ilmenite will be more of a problem. For regolith that is 10 percent by weight ilmenite, the slag waste produced will be on the order of 80 percent of the ilmenite or 3200 metric tons per year. Slag waste will contain much larger and more angular particles, which are less suited to ballistic transport. If the iron is extracted, the slag waste drops to 40 percent or 1600 metric tons per year. These figures are based on 100-percent separation efficiencies.

Costs and Time Line

Terrestrial three-drum slushers are relatively inexpensive yet rugged. A terrestrial slusher with the production profile outlined above costs on the order of \$100 000. While the lunarized version proposed here adds several features to the terrestrial model, the redesign, addition of control circuits, and testing could be accomplished for less than \$10 million. The same design simplicity that lowers the cost of operation will help keep down the research and development cost of the slusher.

After a mining site has been selected and a lunar base has been built, placing the slusher in operation is simple and can be accomplished in about 6 months. Setup time would include final operational testing on the Moon.



How an Archimedean Screw Works
This modern schematic drawing shows how an Archimedean screw works. As the handle (a) *is turned, a certain amount of water* (b) *is brought into the helical screw, which then brings the water up to a reservoir or trough*

***Ceredi's Pump** (concluded)*

Now, in 1565, a Renaissance agricultural engineer named Giuseppe Ceredi patented an Archimedes pump He systematically described the installation and use of batteries of these pumps for both irrigation and drainage But we wonder how he could be given a patent for a known device

When you compare Ceredi's dimensioned drawings, flow calculations, and economic analysis, with the almost unreadable Roman descriptions, you begin to see why Ceredi might well have found the idea in the old literature; but he put flesh and blood on it. After Ceredi's work, these pumps were quickly accepted across Southern Europe. They were not, as one author puts it, "something that would be created spontaneously by peasants " And they certainly weren't something that people would take up naturally in a world that didn't want to mix straight-line and rotary motion.

Ceredi had a right-brain ability to visualize He had a left-brain ability to execute and organize detail. But he was also able to break the straitjacket of Aristotelian thinking A few years later Galileo took up full-scale combat with Aristotelian ideas of motion. And Ceredi's reinvention of Archimedes' pump was a harbinger of that philosophical revolution

Design, manufacture, and testing of a fully operational machine is a modest, well-defined task.

Conclusions

Any startup project in a new environment will have many unknowns. We do not even know all the questions, much less the answers. Mining ventures are very risky here on Earth and most of them fail. The space environment with its many unknowns adds greatly to the degree of difficulty. Keeping the project small, well defined, and simple will help ensure success.

Humans' experience working in space is very limited; our experience in nonterrestrial mining does not exist. Consequently, one significant but indirect benefit of the LOX-to-LEO project will be the experience gained in exploiting lunar materials. This experience will be the basis for later, more ambitious projects, either on the Moon or on other bodies.

Whatever lunar mining method is used, the slusher or something else, must be kept as simple as possible because simplicity means lower costs. The slusher is not particularly efficient or flexible, but it is simple and cheap.

The LOX-to-LEO project is very small compared to terrestrial operations, even small gravel pits. The small size allows consideration of nontraditional methods such as the slusher. The simplicity of the slusher has great advantages in a small operation. If a larger lunar operation is desired, consideration of other methods is mandatory. For example, machines such as the continuous miner should be particularly suitable to mining regolith. The continuous miner has wide application and has been proven in terrestrial coal mines. Traditional methods such as the truck-loader combination can also come into play. This mining combination has long been the workhorse for a wide variety of terrestrial mines.

More complex lunar mining methods may have a greater terrestrial transfer potential. A fully automated machine may find a significant terrestrial market. If so, such methods could amortize their development costs by supplying a wider market than the Moon.

The slusher itself has unresolved problems, even for the small LOX-to-LEO project. Only a few of these problems have been mentioned here. To ensure success, any lunar mining method must solve these problems effectively. Problem definition for a lunar mine has only just begun.

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Asteroid Mining

Richard E. Gertsch

The earliest studies of asteroid mining (e.g., Johnson and Holbrow 1977) proposed retrieving a main belt asteroid. Because of the very long travel times to the main asteroid belt, attention has shifted (Billingham, Gilbreath, and O'Leary 1979, O'Leary 1983) to the asteroids whose orbits bring them fairly close to the Earth. In these schemes, the asteroid would be bagged and then processed during the return trip, with the asteroid itself providing the reaction mass to propel the mission homeward. A mission to one of these near-Earth asteroids would be shorter, involve less weight, and require a somewhat lower change in velocity (ΔV). Since these asteroids apparently contain a wide range of potentially useful materials, our study group considered only them.

Asteroid Materials and Properties

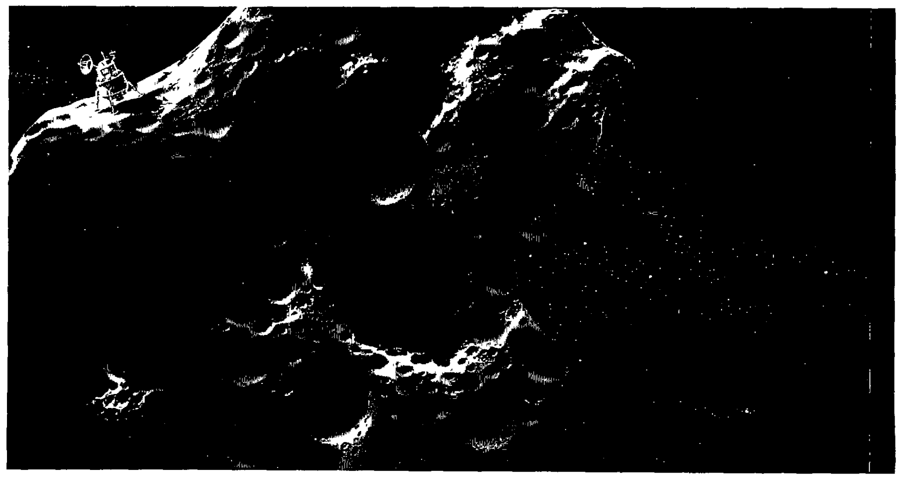
The forces driving the consideration of asteroid mining are their varied materials and favorable retrieval ΔV (see John S. Lewis's paper in this volume). Combining information from spectral studies of asteroids and laboratory analyses of meteorites, investigators have postulated near-Earth bodies rich in volatiles (water, halogens, and organics) and metals (structural, precious, and strategic). While no asteroid prospect has yet been identified, the possibility of obtaining such materials for cislunar operations from a source requiring low ΔV is exciting and should be pursued.

Furthermore, samples in the form of carbonaceous chondrites and similar classes of meteorites indicate that their parent asteroids may have favorable mechanical properties. Some of these materials break up easily at pressures as low as a few bars (10^5 N/m^2) (see table 17 in John Lewis's paper). This breakup pressure is much less than that for most terrestrial materials. For example, some material can be crushed by hand. Although other asteroids may be fundamentally tougher, impacts may have broken up their surfaces into regolith (soil). Thus our study group came to believe that material from a near-Earth asteroid should be easily excavated and rather easily crushed by mechanical comminution equipment already developed for terrestrial applications.

Asteroid Mining

Asteroids have resource potential, notably the potential for providing water, which can be decomposed into hydrogen and oxygen for propellant use. Asteroids may have rough cratered surfaces, as illustrated in this painting. If they are water-rich, they are likely to be similar to carbonaceous chondritic meteorites, which are very black, with extremely low albedos. Such asteroids may be rather soft and friable and thus easily mined.

Artist: Dennis Davidson



Asteroid Mission Selection

While the latest studies of retrieval and processing methods indicate that the project is feasible, the selection and the execution of an asteroid return mission are still fraught with problems. These problems stem from two basic causes: no candidate asteroid has been identified and the long trip time imposes severe limits on the mission. The results seem attainable but only with much more work.

Identifying an Asteroid Prospect

From the perspective of the terrestrial mining industry, lack of a specific asteroid candidate or prospect means that no project exists. Mining projects are so sensitive to actual site characteristics that an asteroid mining mission cannot be justified on circumstantial evidence. This is particularly true of an unmanned mission, where everything must work properly the first time and without human intervention.

Confidence that a feasible asteroid prospect exists in the near-Earth environment is based on statistical analysis. Given the known distribution of near-Earth asteroids and studies of their compositions, it seems probable that a candidate can be located, if enough resources are applied to the search effort (see Michael J. Gaffey's paper in this volume). Physical properties of prospective candidates—mineral grades, mineral variability, specific mechanical characteristics of the asteroidal material, and orbital characteristics—must be determined before significant development of an asteroid mission proceeds.

Nevertheless, a basic understanding of what an asteroid mission might entail is readily at hand. Using the possible orbits, mineral compositions, and mechanical properties of the near-Earth asteroids, one can construct a range of potential missions. The feasibility of such a mission can be established and comparison can be made to a lunar mission, such as the LOX-to-LEO project. Sensitivity analysis of asteroid mission profiles and comparisons to lunar projects can begin almost immediately. Criteria can be developed that will guide selection of candidate asteroid bodies. The expected range of flight characteristics, combinations of ore grades, ore types, mechanical properties, flight durations, and transportation costs can be determined and the range compared to that of a lunar project.

Long Mission Duration

Long travel times to near-Earth asteroids pose significant economic and operational problems. Physical sampling of the candidate body would take as long as the mining mission, so the flow of risk-reducing information is slow. The sampling mission would take a year or more, there may be a long wait for the next mission window, and then the mining mission would take another year or more. Thus, the lead time could be very long. When the mining mission finally flies, an expensive mining plant would have been in orbit a year or more before use. This unproductive time significantly raises the mission's cost. The round-trip time of 2 years or more lowers the rate of return on investment in plant and equipment.

Mission feasibility depends on the right choice of three basic types of missions: a long-duration manned mission, an automatic or teleoperated mission, or a mission in which the manned portion accepts high ΔV and the equipment arrives by slow Hohmann transfer orbit. Determining the proper choice will require extensive research and development, which, of course, increases mission cost. Each type has its advantages and disadvantages, both during the mission and in later technology transfer. The basic tradeoff question—manned or automatic/teleoperated—has yet to be answered.

Manned Versus Automated Missions

Manned Missions

While the problems and expense of a manned mission are obvious—long-term exposure to zero gravity, exposure to dangerous solar radiation, designing controlled ecological life support systems, and man-rating a deep space vehicle (just for starters)—our study group, with its terrestrial mining perspective, suspects that an asteroid mining mission will require human miners. The reason is our skepticism about the ability to economically automate such a mission. Not only has progress in terrestrial mine automation been slow, but also the prospect of applying such technology to an environment with so many unknowns is daunting.

Automated Missions

The benefits of automation are derived from economic considerations and not simply from eliminating people from the production loop. If automation decreases production costs, it should be used. This principle is important even in highly automated industries such as automobile manufacturing. Tasks that are repetitive and boring yet require precision are the best candidates for automation. In this realm, the experience of General Motors illuminates the point. GM's new, largely automated assembly plant has yet to reach production goals and has a myriad of problems. Increasing the production rate and maintaining the required quality while lowering or maintaining production costs justifies the increased capital cost of automation.

Some mines, particularly longwall coal mines, have successfully achieved partial automation of a relatively repetitive mining system. It was accomplished in small steps: One easily defined machine operation or task was automated while the rest of the operations remained manual. After debugging and redesign, the automated operation achieved the required degree of reliability. Then, another candidate for automation was selected and the process was repeated. Over several years, a reliable and integrated but not fully automated system may thus be painstakingly built. In general, terrestrial mine automation has been confined to remote sensing of mine parameters, such as ventilation and equipment status, and production monitoring.

Complete mine automation has been shown to have too great a capital cost to be effectively amortized over the production life of a mine. Furthermore, mining operations have a much greater number of degrees of freedom than does automobile manufacturing. Besides increasing capital (and R&D) costs, operations that are not exactly repetitive have more automation problems than do repetitive operations. Thus, mining costs are not lowered by automation as much as product manufacturing costs are. The fact that the harsh mining environment is much harder on equipment than is a closed plant environment only aggravates the problem.

This experience does not close the door on automatic/teleoperated asteroid missions. It does indicate caution when contemplating these missions. The automatic/teleoperated asteroid mining equipment must work perfectly. Even small equipment failures cause the mission to fail. An expensive R&D effort is needed to ensure such perfection. As with the lunar case, the lessons learned in flying an automatic/teleoperated asteroid mission may find extensive terrestrial application, helping to amortize the large R&D costs.

A Manned Alternative

One possible compromise in the manned/automated tradeoff is to send the equipment on a low ΔV flight and launch the human operators separately on a much shorter, high ΔV flight. The astronauts would mine the body, start the materials on a slow trip back to cislunar space, and themselves make a fast trip back. It should be noted that any manned mission would have the possibility of refining some or all of the fuel required for the return trip.

Teleoperated Missions

Teleoperation resolves some of the difficulties of automated operation. A greater range of the unforeseen problems the system will encounter become solvable. However, actions are carried out by the same actuation devices in both automation and teleoperation. This fact imposes limitations in mining operation control. The Viking lander case is illuminating. The Viking mission, which cost about $1 billion (in 1970 dollars, about $3 billion now), included an extendable scoop experiment that was teleoperated. Although the scoop was relatively simple in design and operation, with few degrees of freedom, first attempts to actuate it failed. A good deal of evaluation and effort ensued before the scoop was successfully operated.

Teleoperation from Earth would be somewhat hampered by a control delay due to the long distances and the speed of signal propagation. However, it seems likely that the effect could be overcome.

Mining in Zero Gravity

Although it might seem easier to move materials in zero gravity than on Earth, inertia, not overcoming gravity, is the major effect to consider. Little experience has been gained in weightlessness. One sample problem is that of holding fracturing and excavation tools to the face of an asteroid. On Earth, equipment hold-down is accomplished solely by gravity. Another sample problem is containing the excavated material, either large or small fragments. Rock fracturing places an initial velocity on the broken material. On Earth, gravity quickly collects the broken rock. In weightlessness, the broken rock will behave like out-of-control billiard balls, a potentially destructive game. Furthermore, the fines that are always generated by rock fracturing may obscure vision and clog equipment. Our study group did not have time to consider the full significance of working complex equipment in zero *g*, but we note that this problem needs in-depth study.

A Conceptual Asteroid Mining Method

The study group did not have the time or the resources to fully design a baseline asteroid mining method. This incomplete concept of an asteroid mining method is intended to illustrate how some of the problems could be overcome. As with the lunar proposal, the concept should be used to promote discussion of asteroid mining problems, but not to promote the method itself. Assuming that the ΔV for the available asteroid is small and that only a modest amount of material is needed, I propose the following method to accomplish a first mission.

After arriving at the asteroid, the operators place one or more cables around the body. The asteroid proposed to the group for study was no more than a few hundred meters in diameter. Placing a cable around the body appeared to us much easier than anchoring the end of a shorter cable. Anchoring in rock can be a difficult process. If augering is used in weightlessness, a method must be devised to hold the augering tool down while it is working. The most desirable asteroids have very low strengths, good for mining but poor for anchoring. Quite long cables are possible, on the order of 1000 meters. The cable is easily placed and provides easy movement of the mining tool. One disadvantage of a long cable is the mass; for example, a cable 1 inch in diameter weighs 1.6 pounds per foot on Earth (has a mass of 2.4 kg/m).

The cable holds a cutter head or other rock-fracturing tool in place and provides sufficient working force for it. The cutter head is designed to excavate in addition to fracturing the soft rock. A conical Kevlar collection bag is placed over the area to be mined and is held in place by the same cable (fig. 24). The flexible bag holds its shape because of the rotation of the asteroid. The spin also aids in collecting the fragmented asteroid material.

The cutter head travels back and forth along its restraining cable, cutting material until the collection bag is filled (fig. 25). The cutter is similar to the coal shear currently used in longwall operations but is designed to overcome the asteroid's low gravity and fling material past synchronous orbit so that centripetal force effects collection. Dust production around the cutter head remains a problem. Dusty environments obscure vision and thus increase problems in controlling teleoperated systems or in monitoring automated systems.

However, direct vision may not be so important on a body that proves to be homogeneous in structure and composition.

After the required amount of material is collected in the bag, it is "lowered" away from the body, allowing the bag and material to steal angular momentum from the asteroid. For low ΔV return flights, there may be sufficient energy available to slingshot the load back to Earth. Deceleration at Earth could be accomplished by aerobraking. The collection bag might be designed to act as an aerobrake shield in addition to being reusable. The bag could also serve as a retort for carbonyl or other types of processing during return.

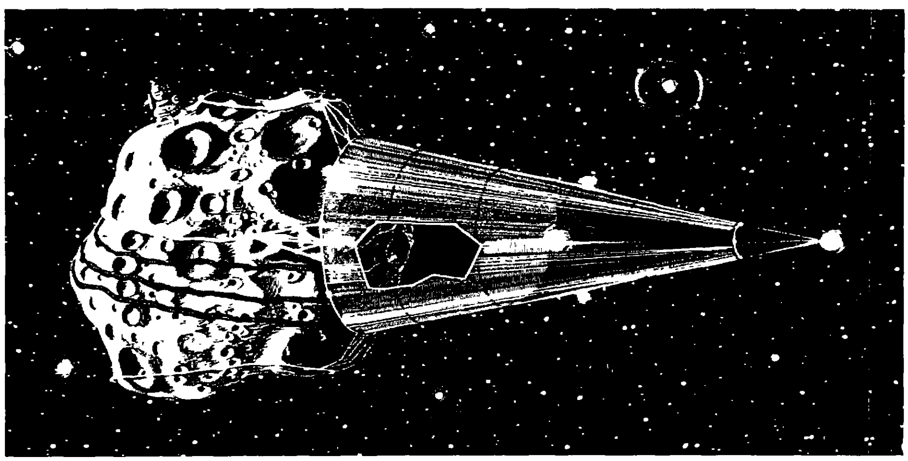


Figure 24

Concept for an Asteroid Miner

The shear breaks material and throws it away from the asteroid into the collection bag. The bag is moved when the shear moves to a new mining area. The collection bag can be used to transport the material to the Earth. The bag could also be used as an aerobrake shield or a processing container.

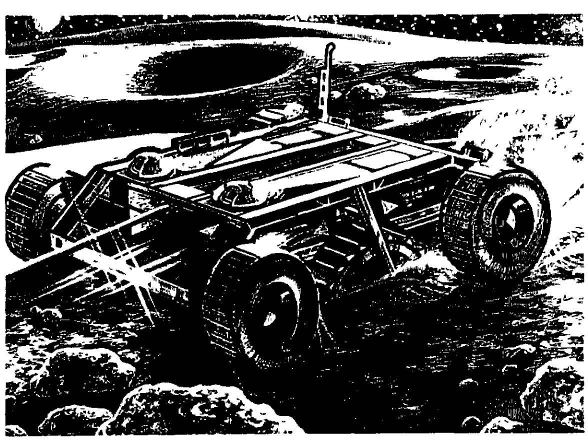


Figure 25

Detail of the Shear

The shear is derived from coal-cutting technology. It performs a dual role: it cuts the asteroid material and throws the material into the collection bag. In this illustration, the wheels are too small; larger, high-flotation wheels will help negotiate rough terrain. There should also be chutes to direct material past synchronous orbit and into the bag. And the shears conflict with the wheel path; they should be either inside or outside the wheels.

An alternative, but basically similar, method still uses the bag and cable. However, a large block of asteroid material is collected, not by mechanical excavation but by blasting material into the bag. Instead of a shear, which could have trouble negotiating the asteroid surface, an explosive is used. The cable holds in place a drilling machine, which drills a series of blast holes. The drill holes and charges are carefully designed to excavate a large section of the asteroid. The explosive charges break out the desired amount of material, and the force of the explosion moves the material into the collection bag. Pattern drilling designed to create shaped explosions has achieved some success on the Earth and is finding more applications. The explosive method appears simpler in equipment and operation than the shear, but the blasting must have a very high degree of control. Uncontrolled fragmentation of the cabled body would be a disaster. I have not considered a suitable blasting agent. The reader can visualize this alternative method by imagining a drill rig instead of the shear in figures 24 and 25.

While the sizing of the return loads requires further study, the same basic mining scheme should be able to handle a range of sizes. It is not completely clear whether one large load or several smaller loads would be better, although several smaller loads might be more manageable, while allowing more flexible return flight plans.

Conclusions

Because it appears to be easier and cheaper to accomplish, the lunar mine is probably a better first project to exploit nonterrestrial materials than is the asteroid mine.

While not causing any increased transportation costs, the long, slow travel to and from the near-Earth asteroids would decrease the rate of return on capital investment.

As in the lunar LOX-to-LEO project, the asteroid mining system must be kept as simple as possible. Simplicity eases problems and lowers the costs of development, equipment, and operations.

A manned mission would make the mining operation much simpler, but it would greatly increase the complexity and cost of the deep space transport vehicle.

Teleoperation seems a good compromise between automation and manned missions, but the choice requires much more study.

Even if specific space program goals or higher costs eventually preclude an asteroid mission, the rich and varied asteroid materials require that the option of mining an asteroid be studied. Given a goal of providing a range of materials for use in cislunar space, lunar projects must be demonstrated to be superior before asteroid missions are abandoned.

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Mining Nonterrestrial Resources: Information Needs and Research Topics

Jaak J. K. Daemen*

The following research topics have been generated by my reading of the draft reports "Exploring, Evaluating, and Mining Nonterrestrial Resources," "To Build a Mine," "Asteroid Mining," and especially "A Baseline Lunar Mine." For a mining engineer like myself who is totally unfamiliar with nonterrestrial operations, this is a fascinating and stimulating opportunity to take an entirely different viewpoint on operations that usually seem humdrum and routine. Being forced to reevaluate the basics might be as productive for our mining on Earth as it is necessary for nonterrestrial operations.

This paper presents an outline of topics that we need to understand better in order to apply mining technology to a nonterrestrial environment. The proposed list is not intended to be complete. It aims to identify representative topics that suggest productive research. Such research will reduce the uncertainties associated with extrapolating from conventional earthbound practice to nonterrestrial applications. No attempt is made to rank the topics. One objective is to propose projects that should put future discussions of nonterrestrial mining on a firmer, less speculative basis.

I offer no details about the actual pursuit of the various research topics. Each one could be approached by a fairly standard method; e.g., starting with a comprehensive literature survey, identifying relevant technical specialties and authorities in the field, detailing research needs, initiating specific projects, reviewing progress, making theoretical analyses, eventually culminating in system designs and experimental trials. It would seem highly desirable to have close interaction between mining experts and space experts, so that no easily avoidable oversights are made in these studies.

I have not used a formal analysis of information needs to select research topics; I make my suggestions purely on the basis of professional judgment. An explicit investigation of information needs and of their relative significance within an overall nonterrestrial mining program would be a desirable step in initiating research. An alternative method of initiating and scoping research, which might take less time, is to present issues to a group that includes both mine equipment designers and operators and space equipment designers and operators.

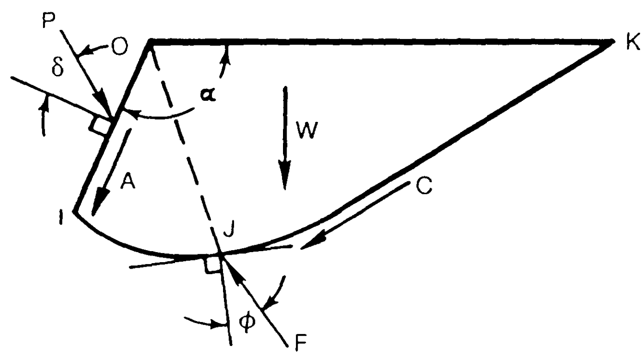
*Department of Mining and Geological Engineering, University of Arizona, Tucson.

The topics identified are inconsistent in terms of their depth and scope. Some have been included to illustrate broad areas that need review; others, to illustrate much more narrowly focused items. Although this inconsistent scale results in some overlap among topics, I think it is appropriate because it points out that there are uncertainties in need of resolution at many different levels of technical detail.

Williamson (1985) has suggested that lunar-based mining may become operational by about 2020, and Glaser (1983) has suggested that nonterrestrial resources may be used even earlier. Profound changes may be required in equipment and in modes of operation to fulfill these suggestions. Now is the time to at least start evaluating whether or not such changes will be needed.

This list of proposed research topics is assembled and discussed from a mining engineering point of view. It is aimed at identifying and clarifying some typical information needs and uncertainties that will require resolution in order to implement mining practices on the Moon or in other space environments. We must recognize that much of the proposed research could make a substantial contribution to future development of mining on Earth. This point deserves emphasis for two reasons: First, technology transfer to terrestrial applications is an explicit NASA mission (stated, for instance, by Firschein et al. 1986, appendix), mandated by Congress. And, second, if the mining industry clearly recognizes the potential benefits for its own future, it is far more likely to cooperate in productive research. The potential for such mutual benefits needs to be expressed directly and specifically, because such potential may not be self-evident to the industry. In fact, a more likely reaction is serious doubt as to whether such "exotic and far out" investigations have any bearing at all on conventional commercial practice. At some point in the future, it may be well to revisit the topic of nonterrestrial mining from a terrestrial technology transfer perspective, focusing on the benefits such a program might deliver to the state of the art of mining technology.

1. The influence of gravity on mechanical excavation technology and on the performance of associated equipment



Key:

A = the adhesive component of the resisting force; it acts along the surface of the plane OI where the soil ruptures
C = cohesive strength of the soil
P = the frictional component of the resisting force; it acts at angle δ
δ = soil interface friction angle
F = the resultant of the normal and frictional forces
ϕ = angle of internal friction
W = weight of the soil being dozed
OIJK = body of soil being pushed up and out

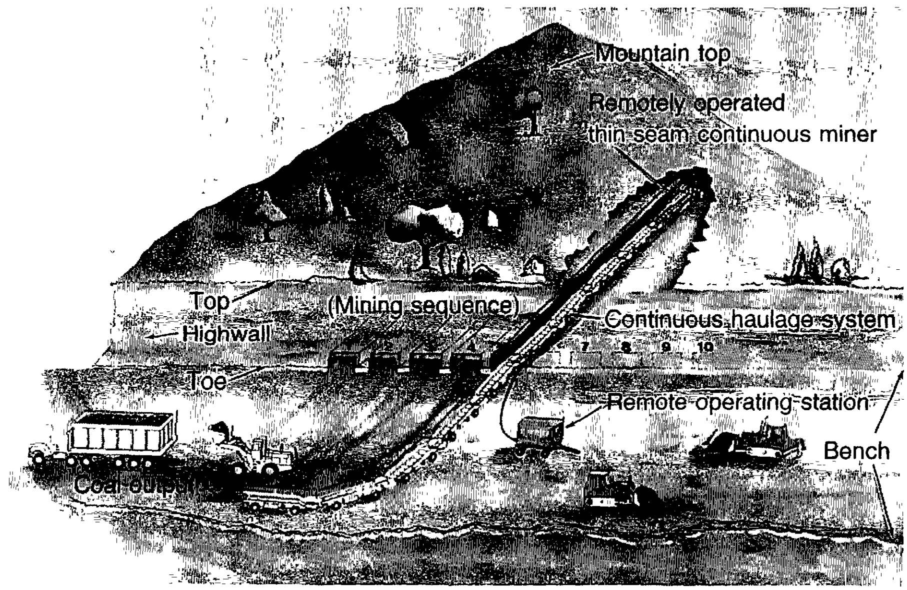
Force System Used for Plastic Analysis of Soil Gathering by Bulldozer

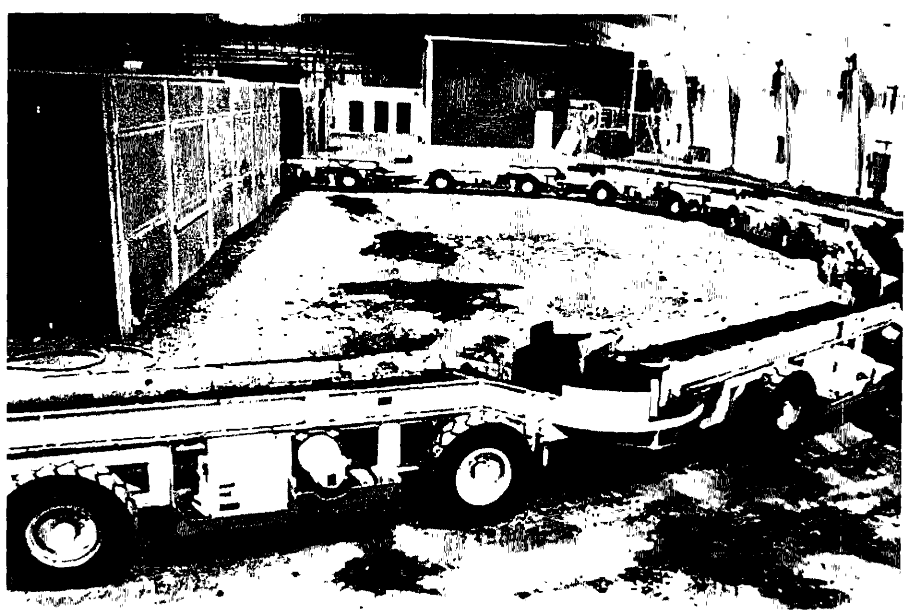
The frictional (P) *and adhesive* (A) *resisting forces, as well as the weight* (W), *depend on gravity. It is probable that the resisting forces are also influenced by operation in a vacuum.*

From Hettiaratchi and Reece 1974, as modified by Karafiath and Nowatzki 1978, p. 247.

Gravity force components enter into the mechanics of most excavation and loading methods. The significance of gravity is likely to differ with the excavation method, particularly with the mode of operation and with the configuration of equipment. Because differences in gravity will be significant between nonterrestrial and conventional earthbound excavation and loading, it would be desirable to evaluate the sensitivity of excavation and loading technologies to gravity. This comparative assessment should include such major performance aspects as power requirements, capacity, productivity, and breakout power. Classifying these aspects with respect to their sensitivity to gravity will provide insight into the relative performance of various systems under significantly different gravitational conditions. Such a classification will help identify preferred excavation methodologies for nonterrestrial applications. This assessment of the impact of gravity on excavation performance will also assist in identifying needed equipment design changes and in establishing correction factors for estimating production figures in a low-gravity environment.

2. The status of remotely controlled and automated mining





a. Computer-Based Remotely Controlled Highwall Mining System (HMS)

b. HMS Continuous Haulage Subsystem During Surface Evaluation

From Kwitowski et al. 1988.

The degree to which nonterrestrial mining operations will be run automatically or under remote control (i.e., the extent to which people will need to be present at or near the mining operation) will have a major economic and logistical impact on the type of operation that can be implemented. Remote control over very short distances (that is, with an operator not more than tens of meters from the equipment) has become readily available for mine face operations (continuous mining of coal; longwall mining; drilling; train, truck, and loader movements; etc.). There has been some success in running underground operations from a great distance [see, for example, the article in *Coal Age*, vol. 92 (1987), no. 8, p. 61], admittedly on an experimental basis.

Even a cursory review of recent mining literature reveals the industry's considerable interest in the subjects of remotely controlled and automated mining (e.g., Atkinson, Waller, and Denby 1987; Hopkins 1987; Scales 1987; Stricklin 1987). It appears virtually certain that considerable progress will be made in these areas in the near future. However, we must acknowledge that highly optimistic announcements about forthcoming mine automation have been made repeatedly, and for at least two decades.

Given the potential importance of automated and remotely controlled mining for nonterrestrial operations, I think it appropriate to recommend an intensive effort to evaluate the current state of the art of such technologies, with emphasis on operations in hostile environments. Mining experience has shown that the environment poses severe problems, especially with regard to transducer performance (see, for example, Atkinson, Waller, and Denby 1987 and Stricklin 1987). I propose that an interactive investigation of such problems with authorities in other fields would be beneficial in identifying possible solutions. Specifically relevant may be remotely controlled equipment for handling nuclear materials, especially for reactor cleanup operations (Kring, Herndon, and Meacham 1987), as well as sensors, transducers, and transmitters developed for the space program (Stuart 1983; Wagner-Bartak, Matthews, and Hill 1983; Firschein et al. 1986). I think it likely that an integration of already existing knowledge may result in readily available improvements to the control systems typically used in mining.

Similarly, it may well be that cost considerations have so severely affected mining systems design that their reliability is unacceptable for space operations. Economic tradeoffs in nonterrestrial mining are almost certain to be different from those in earthbound mining. Hence, it may well be that the reservations and concerns about control engineering which have been generated by mining experience may not be appropriate to space designs. An obvious first step in resolving these uncertainties is simply to assemble a group of experts with relevant backgrounds and have them discuss the problems.

3. Environmental effects on lunar surface mining

Environmental factors such as temperature, air pressure, dust, and visibility have a significant impact on mining operations and equipment. Of most immediate concern is the difference in temperature and atmosphere for nonterrestrial mining as compared to conventional earthbound mining. This difference has significant implications. The cold of the 2-week night on the atmosphereless Moon virtually eliminates the possibility of nighttime operations with conventional equipment because of the problem of material brittleness. And the heat of the 2-week lunar day, unshielded by an atmosphere, will impose demanding cooling requirements. A team of space equipment designers and mine equipment designers should be able to identify mechanical and electrical problems and potential solutions, as well as the redesign needs implied by these solutions. Daytime lunar surface operations, particularly rock loading, could be severely affected by perception problems induced by the bright sunlight and constantly changing shadows (discussed by Firschein et al. 1986, p. 112).

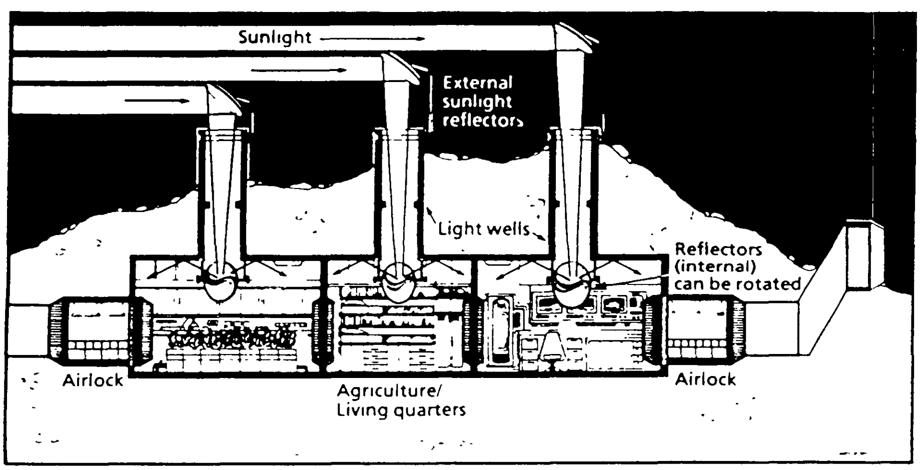
4. The applicability of conventional mining methods and equipment to lunar mining

When one considers the applicability of Earth technology to lunar mining, one can focus rapidly on a likely lunar project and retrofit an available mining method to meet the characteristics of this particular project. However, I propose that program benefits might derive from a comprehensive analysis, at a preliminary scoping level, of the applicability of conventional earthbound mining methods and technology to lunar operations. Such an analysis could proceed from a comprehensive matrix, listing mining methods along one axis and lunar features (such as logistics, gravity, vacuum, temperature, perception problems) likely to affect mining along the other axis.

To each mining method, one can assign weights for the various differences between terrestrial and lunar operations. Initially the weighting could be done on the basis of expert judgment. But as soon as possible the weighting should be based on a numerical analysis. For simple mining methods, the weights could be based on the mechanics of the system. For complex methods, the weighting may require a comprehensive numerical simulation of an entire sequence of operations. This technique would allow a formal assignment of level of difficulty likely to be encountered in applying the terrestrial technology to the lunar situation.

An effort of this type should be iterative. The initial list may include technology that is entirely inappropriate or exceedingly difficult to modify or implement. In parallel with such iterations, one might also expect a progressive refinement in the information needs about the most likely operational conditions.

5. Underground construction methods for lunar application

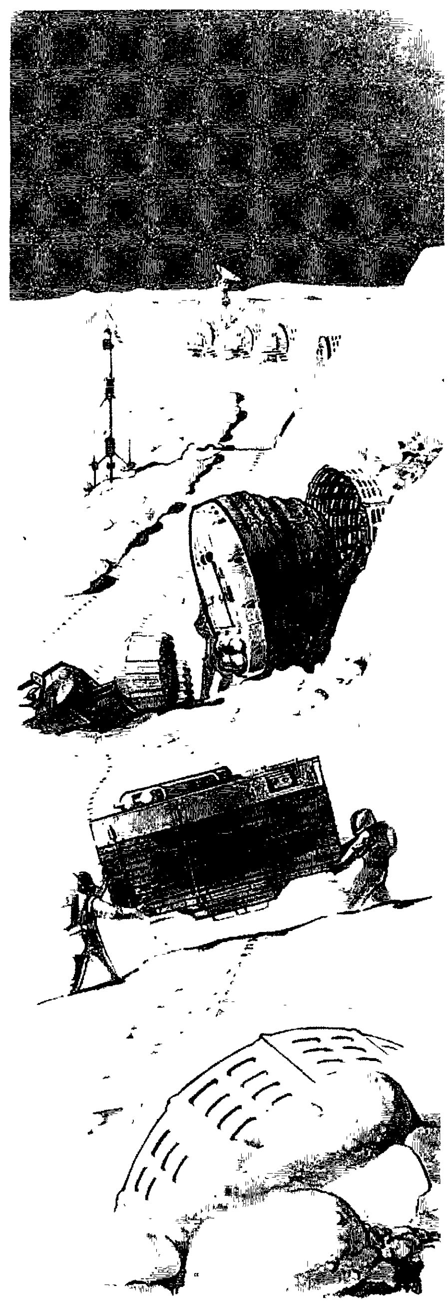


a. Underground Mining

Although the baseline lunar mine was conceived to be a strip-mining operation, there may be locations where the regolith is so thick that it could be mined by some undercutting scheme. Excavations could be driven below the material to be mined, and the material could be drawn into the excavations for milling. The light wells in this illustration could correspond to draw points for bringing material directly underground, and the agriculture/living quarters could correspond to the scene of all subsequent mining operations, which would thus be shielded from the hazards of the lunar surface environment.

As pointed out under topic 3, the environment will impose severe limitations on surface operations on the Moon. It therefore appears fully warranted to investigate the feasibility of moving mining operations underground. Lunar scientists can probably provide information on the subsurface lunar temperatures, and this information may encourage the investigation of going underground.

Operating underground on the Moon raises a number of intriguing questions. Conventional support systems such as concrete, steel, and shotcrete are likely to have an



b. Tunneling for Lunar Habitats

Perhaps the tunneling techniques developed for mining could be used to construct lunar habitats. The two astronauts in this illustration provided by Encyclopaedia Britannica *seem to be having no difficulty carrying a capacious pressurizable module for a tunnel. In gravity only 1/6 that of the Earth, the required weight-carrying strength of equipment as well as people could be reduced to 1/6 that required on Earth.*

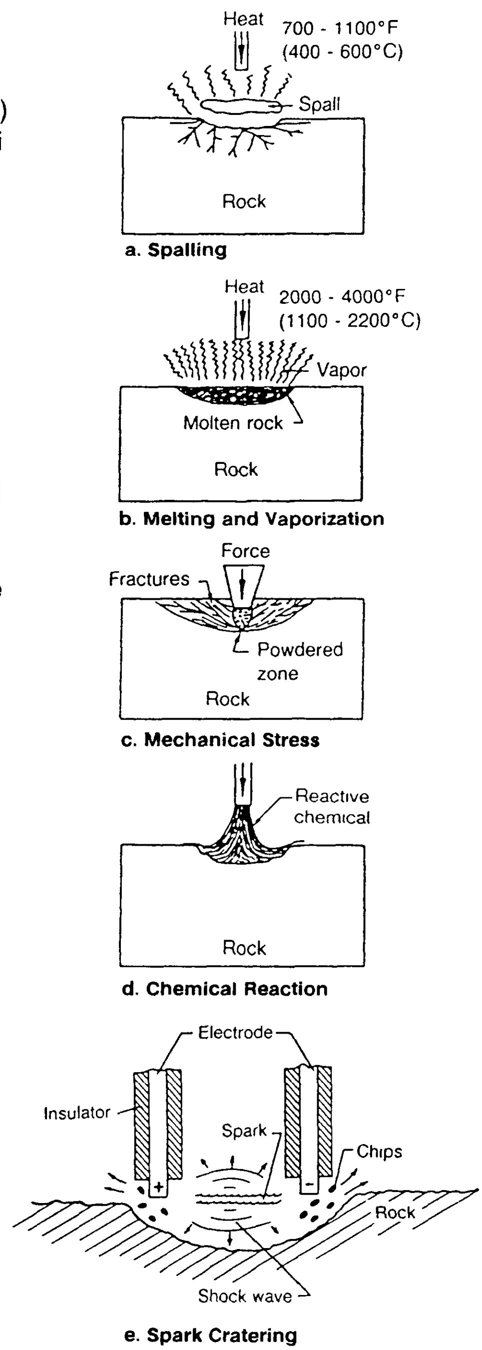
even less favorable weight-to-performance ratio than on Earth. Hence, the economics of their application need to be investigated in detail. As I briefly outline under topic 7, the preclusion of conventional support systems would not necessarily exclude underground construction in weak or disintegrated ground, but it would put a premium on developing reinforcement methods, integrated with the construction cycle, which minimize weight requirements. Given that the most frequently encountered and most severe problems for earthbound underground construction and mining arise from unexpected conditions (that is, sudden changes in ground quality), it is virtually certain that underground lunar construction should be preceded by markedly better site investigation and characterization than is the norm on Earth.

Underground construction on the Moon should have some significant advantages when compared to earthbound practice. Most underground construction problems are associated with water, because of excessive pressure, excessive flow, or both. Indeed, a standard if somewhat overstated saying among engineers holds that "a dry tunnel is an easy tunnel." The absence of water will facilitate underground construction on the Moon. Moreover, the certainty of not encountering water will eliminate the need to plan for the contingency.

The increased friction (more intimate physico-chemical bonding) in vacuum (Karafiath and Nowatzki 1978, p. 130) should assist in stabilizing underground excavations. It may also make excavation somewhat more difficult, but excavation per se usually is a relatively minor cost factor in underground mining. The low gravity will increase the weight-carrying capacity of equipment and reduce the energy requirements of muck haulage and particularly hoisting. Light levels, and hence visibility, may be easier to control underground than on the lunar surface.

Underground construction on the Moon will differ from underground construction on Earth in a number of important aspects. Its potential advantages over surface construction appear to warrant a comprehensive assessment of its merits. Such an assessment should address all aspects that affect life-cycle costing.

6. Rock drilling on the Moon



Methods for Disintegrating Rock

a. ***Spalling:*** *Inducing high thermal stresses by rapid application of intense heat.*

b. ***Melting:*** *Liquefying rock by raising its temperature.*

c. ***Mechanical Stress:*** *Inducing stresses exceeding strength by applying mechanical forces to the rock.*

d. ***Chemical Reaction:*** *Dissolving rock bonds*

e. ***Spark Cratering:*** *In a variant of c, discharging sparks between electrodes to generate pressure pulses which in turn chip the rock.*

From Maurer 1980, pp. 1 and 509.

Different types of rock drilling are likely to be required on the Moon. Certainly core drilling will be desirable, if not essential, for collecting samples for rock characterization tests. But alternative, much less expensive hole-drilling techniques (in which the material from the hole is not kept intact) may be considered for such purposes as anchoring structures, explosive fragmentation, or even sample collection.

All conventional rock drilling methods, including diamond coring, rotary drilling of soft rocks, and percussion drilling of hard rocks will be affected by differences between lunar and terrestrial operating conditions. Most obvious are differences in gravitational pull, atmospheric pressure, and thermal conditions.

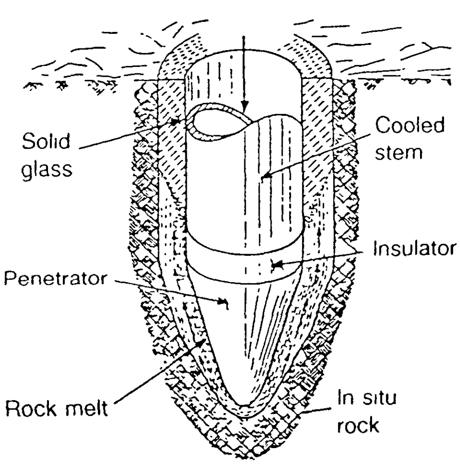
The very low gravitational forces on the Moon are likely to require a thrust system designed to assure adequate drilling progress. This could be a passive (weighting) system or an active (jacking) system. Regardless of which approach is taken, it seems very likely that drilling equipment will require significant modifications in order to provide the necessary thrust.

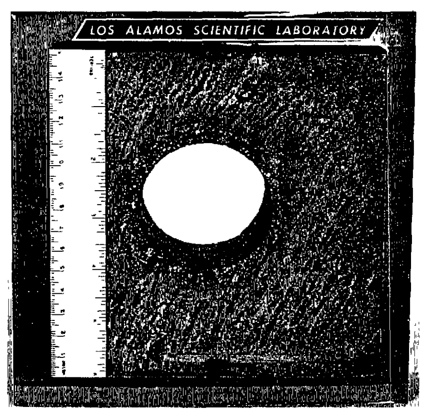
The lack of atmosphere on the Moon will create complications in providing and maintaining drilling fluids. In conventional practice such fluids are needed, in considerable quantities, in order to remove cuttings from the hole and to cool the drill bit. And on the dry and highly fractured surface of the Moon, these fluids would be easily lost. Cooling of the bit, as well as of the drilling motor, may be further complicated by the thermal environment on the Moon. This will certainly be a complication during daytime operations on the surface.

In sum, fundamental aspects of rock drilling are affected significantly. This impact will be reflected in needed changes to drilling equipment and operations. A first step in the investigation will be to determine as narrowly as possible the expected conditions under which drilling will have to be performed. This determination will in turn allow an identification of the basic parameters to be used in evaluating changes in fundamental drilling mechanics and hydraulics. Finally, such changes will lead to equipment modifications, if not to totally new drilling designs.

While this discussion has centered nearly exclusively on conventional drilling technology, I should point out that extensive investigations have been made of numerous, radically different drilling technologies (e.g., Maurer 1980). A variety of reasons, including high conversion costs, institutional inertia, and the fact that most novel drilling methods require large amounts of energy, have so far prevented the widespread implementation of such alternative drilling methods. The novel drilling and rock excavation method that has found most widespread application—water jet excavation—is inappropriate for space applications. For reasons similar to those discussed under the next topic (rock melting), tradeoffs will need to be made between energy use (high for novel technology, low for conventional drilling) and delivery weight (low for novel technology, high for conventional drilling).

7. Lunar construction by rock melting





Consolidating Penetrator

The schematic diagram (Sims 1973, p. 7) shows how this novel drill bit penetrates loose soil or porous rock by melting it. Then the cooled drill stem consolidates the melted rock into a dense glass lining. The photograph (courtesy of John C. Rowley, Los Alamos National Laboratory) shows a hole melted through volcanic tuff by means of a consolidating penetrator. Note the dense (and therefore strong) hole liner.

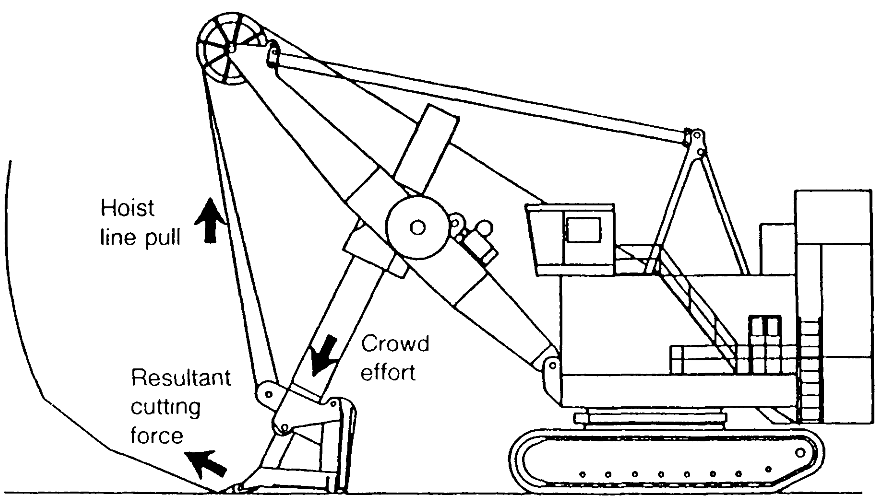
Many aspects of mining may have to be altered profoundly for operations in an environment with low gravity, extreme temperatures, and high vacuum, at locations where direct human access and support will be exceedingly expensive. Because the differences between conventional and space operations may be drastic, it may be appropriate for us to evaluate radically different approaches.

One option that deserves attention is a rock melting system. This rock excavation method has been extensively investigated by Los Alamos National Laboratory (Neudecker, Giger, and Armstrong 1973; Sims 1973; Rowley 1974; Hanold 1977). Rock excavation by melting has been developed to an operational level for small-scale applications (drilling holes) and is proposed for large-scale applications (excavating tunnels).

For space applications, the system has the attractive feature of being self-contained; that is, of requiring minimal deliveries. It can, for example, melt its own liner in situ (in weak ground), thus obviating the need for additional support installation. However, it may require excessively high energy. It is interesting to note that the developers of rock melting for full-size tunneling envisioned the use of nuclear power, and it has been argued that nuclear power is essential for large-scale lunar development (Ehricke 1983).

The rock melting approach option is included here to stress the desirability of taking a broad view to identify appropriate technologies; that is, going well outside the bounds of conventional solutions. Whether rock melting is an appropriate alternative to conventional mining remains to be seen. A scoping meeting involving Los Alamos personnel associated with rock melting would seem a desirable first step to determining whether or not further evaluation is warranted.

8. The implications of vehicle traction on the Moon for mining operations



Simplified Force Diagram for a Conventional Mine Shovel

The cutting force of a shovel is a function of hoist line pull, crowd effort, and front-end geometry. A large machine weight is needed to provide horizontal resistance to slippage during digging.

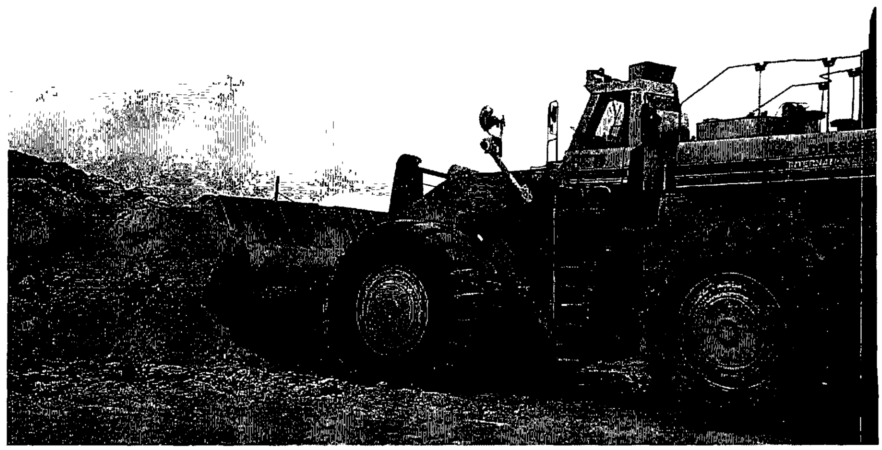
Courtesy of J. D. Humphrey, Dresser Industries

Traction is an important operational aspect of most vehicles. It is particularly important for vehicles that need to exert large horizontal forces; e.g., for excavating, loading, and hauling. Many types of mining equipment are very dependent on the development of adequate traction. This equipment includes excavation equipment such as bulldozer-mounted rippers and scrapers, front-end loaders, shovels, and drills, especially those for drilling angled or horizontal holes.

Comprehensive studies have been performed of vehicle traction on the Moon (among them, Karafiath 1970a,b; Nowatzki 1972). Even though these have addressed the operations of primarily small, lightweight roving vehicles, they provide fundamental insight into the traction of larger, heavier lunar mining vehicles. Moreover, experience with the lunar Rovers has provided an operational record by which to validate the traction models and predictions made for them.

Traction deserves attention because it is a major force needed for many mining operations. Because it is a function of gravity and of friction, the latter affected by vacuum, it will be affected by the space environment. Considerable experience is available to guide further research into this aspect of lunar mining.

9. Moon excavation technologies



Muck Pile

This is an example of a good muck pile, well-fragmented and largely remaining in one heap. Loading would be much more time consuming if the rock were widely dispersed, as it might be by conventional blasting in a low-gravity environment, without air resistance. The loading machine must have sufficient traction (created by both friction and weight) to be able to push the loading bucket into the muck pile.

Lunar mining may involve the removal of various types of ground, ranging from massive solid rock to loose, granular soils. This possibility suggests the need to investigate a range of material-removal technologies. It may be desirable, at this early investigation stage, to distinguish between the fundamental mechanics underlying the technologies and the technologies themselves. Both will be affected by operations on the Moon, but in different ways.

a. Hard rock excavation mechanics

In earthbound mining, hard rock is removed primarily by explosive excavation. Lunar blast design is likely to require significant changes from conventional blasting. An obvious consideration will be the need to control the broken rock pile. It is usually assumed that gravity plays no role in actual rock breakage by conventional blasting, but it plays a significant role in displacement of the broken rock (and thus dominates the shape of the muck pile). Low gravity could result in extremely wide scattering of rock fragments, even more so in the absence of air resistance, and hence lead to exceedingly inefficient loading operations. An interesting challenge may be posed by the need to adjust blasting patterns from the traditional ones to those designed to minimize scatter in a low-gravity and high-vacuum environment.

It is possible that vacuum might affect blasting performance, although it may not be a significant factor in low-permeability rock, at least at greater depths. The breakage induced by blasting is usually attributed in part to seismic effects and in part to gas pressure effects. Presumably gas pressure effects could attenuate much faster in a space environment than on Earth. This could affect fragmentation and almost certainly would affect heave and throw; i.e., rock movement.

Potential impacts of low gravity on mechanical excavation have been discussed under topic 1. Drastically different excavation technologies are summarized by Maurer (1980), and they deserve intense scrutiny for lunar applications.

b. Soft ground excavation mechanics

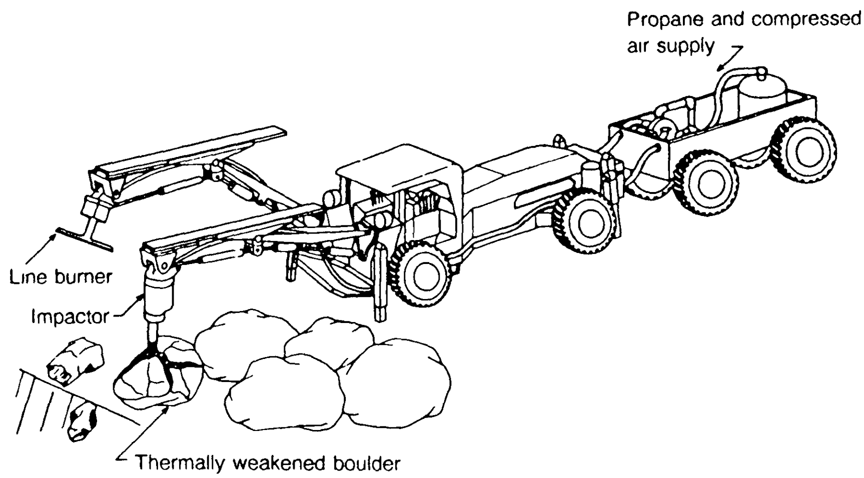
Mechanical excavation of loose, granular material on the lunar surface is likely to be facilitated by the lower gravity in terms of actually lifting the material, although this improvement may be partially offset by increased friction between particles. It is likely that the most significant detrimental effect will be on the forces that can be delivered by the equipment. Reduced equipment weight will reduce breakout forces and sliding stability. It is quite possible that even a simple force analysis of excavation systems will shed considerable light on lunar soil loading requirements and potential problems. Gertsch has suggested that we add mass to lunar equipment by building into it large volumes to be filled with lunar rocks. However, as he notes, the added mass would add to the problem of inertia in mobile equipment.

Thermomechanical Boulder Breaker

A mobile thermomechanical boulder breaker could fragment rock by first weakening it by applying heat (in this concept by means of a burner) and then hitting it with a mechanical impactor.

From Thirumalai, Demou, and Fischer 1975, quoted by Maurer 1980, p 653.

10. Potential asteroid fragmentation technology



Technology for fragmenting rock particles has been researched and developed over many decades. Conventional fragmentation is primarily mechanical. Its effectiveness on a virtually gravity-free asteroid will depend in part on the degree to which the mechanical fragmentation system depends on gravity. We can conceptualize mechanical fragmentation systems that are independent of gravity; i.e., those that work by splitting or pinching. Also available are a variety of explosive, electrical, chemical, and thermal disintegration methods. These methods will impose different logistical requirements, depending on what supplies they need and on how operations are carried out. For example, the efficiency of several fragmentation methods would increase if the fragmentation took place in drill holes. But drilling holes in asteroids will pose unusual problems (see topic 6).

It may be desirable to distinguish between two classes of fragmentation problems, those where a single fragment (or a small number of fragments) is to be removed or reduced to certain dimensions, and those where a large number of particles are to be reduced in size. The latter class of applications is discussed under topic 15, crushing and grinding. The choice of technology most readily applicable to removal or controlled-size reduction of a single large block might well benefit from an evaluation of quarrying practice for building stone. Advanced rock disintegration techniques, some of which should have direct applicability to space operations, are summarized by Maurer (1980).

11. Automation, operator proficiency, and excavation efficiency

Eliminating the need for human operators would significantly enhance the economic attractiveness of nonterrestrial mining. Few attempts have been made at developing fully automated mining excavation cycles; i.e., operations without human intervention. The economic incentives for doing so on Earth are marginal, at best.

Fully automating the mechanical excavation and loading of broken rock is likely to result in drastic productivity losses. It is well established that the productivity of virtually all excavation and loading equipment is highly sensitive to the expertise of the operator. Human judgment and fast response to seemingly minor aspects of rock loading operations are significant production and safety factors. Of particular concern in this context is that misjudgment by an operator can result in serious, even disastrous, consequences, such as cables breaking and machines overturning. Control engineering will have to preclude such occurrences as well as assure a reasonable production level.

The importance of human judgment in excavation technologies suggests a number of avenues for research aimed at identifying candidates for automation and nonterrestrial application. Questions that can be raised include the following: Will the implementation of automatic operation be most difficult for equipment that is most sensitive to operator handling? Should automation be preferentially applied to excavation technologies that are robust or insensitive to operator errors? What tradeoffs are acceptable between automatic control and productivity?

To allow automation, operations should be as simple as possible. This fact, explicitly recognized in the space program (e.g., Firschein et al. 1986, p. 103), unquestionably underlies the mining industry's reluctance even to attempt to automate most excavation methods. The few notable exceptions (longwall mining, tunnel boring) for which automation is being investigated are already fully mechanized (involve minimal human intervention during normal operations). These exceptions tend to be high-production systems. They are prone to frequent breakdown and require preventive maintenance. Maintenance is recognized as a major difficulty in implementing automation (e.g., Firschein et al. 1986, p. 355); it will require major developments in artificial intelligence software and robotics. The need for human reasoning capability is again apparent.

12. The influence of gravity on slusher mining

Gertsch identifies slusher mining as one of the more promising lunar mining methods. The performance of a slusher on the lunar surface (or in underground operations on the Moon) will be affected by the low gravity.

The lighter weight of the scraper (bucket) on the Moon may lower the loading efficiency of the slusher bucket, because the weight influences the vertical penetrating force into the material to be loaded. Conversely, the lighter weight lunar material may flow more easily up into the bucket. It is conceivable that artificial weighting down of the bucket, or a reconfiguration of the cable force system, might be required in order to assure adequate penetration into the lunar soil and to avoid riding of the (empty or partially filled) bucket over the material to be loaded. Conversely, friction, abrasive wear, and power requirements during both inhaul and outhaul may be significantly reduced by the low gravity.

The reduced effective weight of the bucket, which is likely to have a detrimental impact on the efficiency of the all-important bucket-loading phase, might also adversely affect the performance of the bucket as it is hauled in to the unloading point. Assuming a relatively rough and bumpy ride during inhaul, the bucket may not retain its full load. An analysis might suggest a reduction in hauling speed, but this might also affect production adversely. It is possible that bucket redesign and cable reconfiguration might compensate at least partially for the reduced effective bucket weight.

Given the interest by this group in the application of slusher mining to the lunar program, it may be appropriate to outline in some detail steps that could be taken to reduce the need for speculation about the performance of such systems on the Moon.

Obtaining a clear understanding of the mechanics of bucket loading would be a desirable step. This step could be initiated with a comprehensive literature survey. It is unlikely that much fundamental information is available about slusher bucket mechanics, but considerable analysis has been made of the mechanics of similar excavation elements, such as dragline buckets, bulldozer blades, front-end loader buckets, and scrapers. Integrating this knowledge in a framework emphasizing the mechanical differences between terrestrial operating conditions and lunar operating conditions would go a long way towards identifying potential problems. Such an integrating effort should be made by a group with a clear understanding of the fundamental mechanics of the machine (bucket) and material (broken rock). At a minimum, meetings should be organized with experienced bucket designers from various manufacturers. In order to obtain maximum contributions from such personnel, it may be preferable to formally contract for their technical services. Equally important would be information exchanges with operators; e.g., by means of visits to mines.

On the basis of the initial analyses, it should be possible to make preliminary estimates of the influence of gravity on bucket loading performance. This information could in turn form the basis for designing experiments (for example, experiments using centrifuges) to verify the analyses. Similarly, it may be possible to instrument buckets and their cables and chains in order to obtain a better understanding of the distribution of forces during loading. An appropriate iterative sequence of bucket analyses, experiments, and design modifications should provide a considerably improved understanding of bucket mechanics, ultimately leading to adequate bucket designs for drastically different operating conditions.

While I have emphasized slusher bucket development, I should point out that any studies of this type, aimed at an improved understanding of the mechanics of loading broken rock, will be beneficial for eventual redesign of other systems that might be considered for nonterrestrial loading operations. These would include hydraulic excavators, electric shovels, front-end loaders, bulldozers, scrapers, draglines, and clamshells.

13. Wear-resistant materials for space mining applications

Equipment maintenance is one of the most expensive and time-consuming (in terms of production delay) aspects of mining operations. The most critical maintenance aspect of all excavation equipment is the wear rate of excavation elements (e.g., buckets, their teeth, drag cables). Similarly, components of equipment for haulage and for crushing and grinding, which are subject to repeated impact and abrasion, may require frequent resurfacing or replacement. Replacement schedules and parts requirements need to be estimated in order to develop realistic life-cycle cost estimates. If wear parts had to be provided from Earth and if conventional replacement schedules needed to be maintained, the transportation requirements of nonterrestrial mining would be considerable.

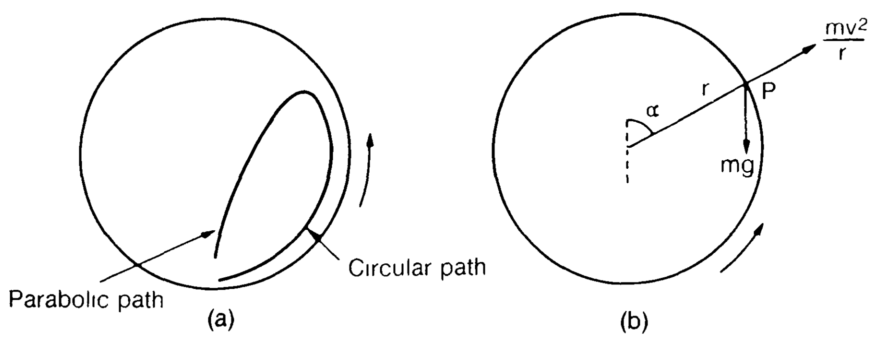
It is virtually certain that the thermal environment, with its extremes of cold and hot, will significantly increase the wear on some components. Less certain, but nevertheless possible, is that increased friction due to the vacuum environment (Karafiath and Nowatzki 1978, p. 130) may contribute to accelerated frictional wear.

Wear components, especially excavation components, tend to be made of very heavy steel alloys. Assuming that in parallel with lunar mining will proceed in situ manufacturing [including production of metals (Ehricke 1983)], it may be worthwhile to consider tradeoffs between transporting high-quality wear parts and producing lower quality wear parts locally.

14. Remote sensing of rock excavation characteristics

The potential of remote sensing to characterize the lunar surface for equipment mobility has been mentioned by Karafiath and Nowatzki (1978, p. 492). The significant impact vehicle traction may have on mining operations has been discussed under topic 8. With respect to mining itself, whether excavating hard rock or scooping up and loading soil, remote sensing will be equally important in determining strength, particle shape and size, interparticle friction, and other excavation parameters. While a final assessment of excavation feasibility will almost certainly require direct physical access, it is clear that remote sensing should be used to the greatest possible extent in determining excavation characteristics of possible mining sites. The importance of remote sensing obviously is well established in the space program, but we should note that interpretation in terms of minability may pose some unusual requirements.

15. Particle size reduction technology for applications in space



Tumbling Mill Action

a. Trajectory of the Grinding Medium in a Tumbling Mill

b. Forces Acting on Particles in a Tumbling Mill

Tumbling mills are widely used to reduce the size of broken rock particles. A particle being lifted up the shell of the mill will abandon its circular path for a parabolic path at point P, *where the weight of the particle is just balanced by the centrifugal force; i.e., where*

$$mg \cos \alpha = \frac{mv^2}{r}$$

This illustration of the forces acting on a particle clearly shows why gravity will affect grinding.

From Wills 1985, p. 186.

Mechanical reduction of particle size is usually not considered part of the mining cycle. It immediately follows the mining cycle, however, and optimizing the total sequence works better than optimizing the mining and milling operations separately.

Crushing is typically the first step in reducing the size of the mined rock. Most crushing systems depend on gravity feed and flow (Wills 1985, ch. 6). Gravity directly affects fragmentation in some systems (Motz 1978). Its influence may not be fully appreciated in others, as it has never been considered a significant variable. The forces acting on particles during crushing in a low-gravity environment will differ markedly from the forces operating in conventional situations. It appears likely that crusher geometries (e.g., jaws, cones, throats) might need to be modified for operations in an environment with drastically reduced gravity or that throughput rates might require considerable adjustment. Increased frictional force components may be beneficial in some crushing systems (Wills 1985, p. 169) but could be detrimental in others.

Grinding particles, either dry or submerged in liquids (Austin, Klimpel, and Luchie 1984; Wills 1985, ch. 7), is usually the final particle size reduction step. It is not obvious how significant the effects on grinding of a low-gravity, high-vacuum environment may be. In the most widely used tumbling mills, particle size reduction is accomplished primarily by impact. Gravity forces enter very explicitly into the design of these tumbling mills (Wills 1985, p. 186). Hence, an analysis of gravitational effects should be straightforward. Such an analysis would be worthwhile because it addresses the most energy-consuming aspect, by far, of size reduction operations. Wet grinding, almost always preferred, clearly would pose problems in logistics (delivering or producing the liquid) and in containing and recovering the liquid.

Particle size classification is an important control procedure applied throughout the milling sequence. Most sizing methods depend on gravity to some extent. The final fine particle size classification most commonly is accomplished by differential settling in liquids, a method that would pose the same problems for space mining as would wet grinding.

The milling operations discussed here deserve consideration along with mining methods in order to optimize the entire sequence. Such an integrated optimization may shift the degree of fragmentation desired from the mining portion of the operation. The desired fragmentation may affect excavation, loading, and hauling.

Conclusions

The applicability of conventional mining technology to space mining can currently be evaluated only on the basis of judgment and speculation. I have presented a list of research topics that correspond to information needs which must be answered in order to put such evaluations on a firmer basis. In many areas, relatively simple analyses of the mechanics of the system and of the impacts on it of gravity, atmosphere, and temperature could add quantitative understanding of the operation of terrestrial mining technologies in nonterrestrial environments. Iterative interactions between space engineers and scientists on the one hand, mining engineers on the other, and the integrating researchers performing the analyses should assure that the investigations stay correctly focused. Such investigations could be of considerable benefit to the mining industry, and this terrestrial technology transfer aspect deserves specific recognition.

I have given examples of conventional mining technologies which might be adapted to nonterrestrial applications, as well as examples of technologies that have not found practical applications on Earth. I propose that two approaches be pursued in parallel: one starting from available technology and identifying needed adaptations; the second starting from likely ultimate objectives and developing solutions unencumbered by conventional practice and thinking.

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PART 2—Beneficiation and Extraction of Nonterrestrial Materials

William N. Agosto

The group that reviewed options for processing nonterrestrial materials was dominated by industrial materials scientists who tried to identify which processes utilizing space materials could be implemented in the near term.

The most practical process seemed to us to be the extraction of lunar oxygen and the extraction of metals and ceramics from the residues of the reduction process. The growth of space activity will be accompanied by increased demand for liquid oxygen for rocket propellant. In particular, any lunar base activity will require tens of tons of oxygen for each round trip to the Moon. And, of course, the oxygen and the intermediary product water will be needed for life support at the base. The reduced metals and ceramics may be considered byproducts or may develop into primary products. Some of the same processes would be directly applicable to recovery of products from asteroids. We also discussed other processes for directly utilizing asteroid metals.

Beneficiation and Oxygen Extraction Methods

Reduction of lunar ilmenite with hydrogen imported from Earth was judged to be an oxygen extraction option that could be implemented in the near term. Ilmenite, an iron and titanium oxide, is the most abundant oxide in the samples that have been brought back from the Moon.

Working for Lockheed Corporation at the Johnson Space Center, I reported the successful concentration of ilmenite in an Apollo 11 soil sample, using an electrostatic separator based on a commercial design and operated both in nitrogen and in a vacuum. This was the first research reported on the industrial behavior of actual lunar material. Additional research is needed to determine the characteristics of a system that could operate on the Moon.

A process not requiring beneficiation, because it extracts oxygen from the predominant silicates, was probably the first process considered for extraction of oxygen from lunar materials. The carbothermal process was developed by Sanders Rosenberg and colleagues at Aerojet-General Corporation in the mid-1960s, before we had been to the Moon. They assumed that ordinary rock-forming minerals, such as olivine and pyroxene, would be abundant, an assumption that proved to be mostly correct. Rosenberg and his colleagues performed a series of experiments demonstrating actual oxygen extraction from simulated lunar materials. In addition, they designed an oxygen production plant and did a parametric analysis of mass, power, and cost. David McKay has combined several of their papers from that period and updated the cost analysis to 1989 dollars. This combined paper presents the basic concepts of the carbothermal process, gives the results of some of the laboratory experiments, and includes the design concept for a lunar oxygen plant. The paper is interesting both because of its historical value in presenting a lunar oxygen plant designed before Apollo 11 and also because the basic concept is still viable today as a candidate oxygen plant for a lunar outpost in the early 21st century.

In a review of proposed lunar oxygen production processes, including carbothermal reduction and electrolysis of basalts, Christian W. Knudsen and Michael A. Gibson, of Carbotek, Inc. (Houston), have concluded that hydrogen reduction of ilmenite is the simplest process proposed. Products of the reaction are iron, titanium dioxide, and water; oxygen is then extracted from the product water by electrolysis. Both batch and continuous-flow fluidized-bed processes for the reaction have been described. Although the preliminary results of bench-level tests on the batch process conducted by Richard J. Williams at JSC seemed promising, further engineering work by Knudsen and Gibson indicates to them that only a continuous process is practicable on a large scale. Knudsen and Gibson also considered hot pressing of the metallic iron and titanium dioxide residues of the reaction into cermet parts and bricks, as outlined by Agosto (1981).

Russell O. Colson and Larry A. Haskin discuss the direct electrolysis of molten lunar material to produce oxygen. In the magma electrolysis process, iron, silicon, or iron-silicon alloys are produced at the cathode and oxygen is produced at the anode. Potential byproducts include ceramics (spinels) and cast-rock products such as bars, beams, and sheets. Colson and Haskin argue that, compared to most other proposed processes, this process requires less energy per unit of oxygen and has the advantage of being relatively simple. Technology challenges include finding container and electrode materials that will withstand the corrosiveness of molten silicates. The work of a number of years has determined some of the fundamental properties of melt conductivity and some of the factors affecting the efficiency of oxygen production.

Solar furnace pyrolysis of lunar basalts in vacuum, as proposed by Elbert A. King and me (1983), is considered another highly promising process for nonterrestrial oxygen production. It does not require reagents imported from Earth. King (1982) demonstrated the process on Earth using terrestrial basalts and samples of the Murchison meteorite heated to approximately 3000°C in a furnace with a solar mirror 2 meters in diameter. Residues of metallic iron and oxides of aluminum, calcium, and titanium indicated the evolution of oxygen and volatile oxides of other elements. A bench-level research program is required to characterize, quantify, separate, and capture the oxygen and other volatiles liberated by the process. Residues of the process include metals (iron), semimetals (silicon), ceramics (Al-Ca-Ti oxides), and feedstocks rich in aluminum oxide for aluminum electrolysis.

Wolfgang H. Steurer, of the Jet Propulsion Laboratory, considered two vapor-phase processes: (1) the volatilization of oxygen by vacuum pyrolysis of oxides and (2) electrostatic separation of metals from high-temperature plasmas of nonterrestrial materials. The high temperatures and reactivities of such processes suggest that the technology will be difficult to develop. However, such processes may prove to be effective.

Metallurgy

David F. Bowersox, of Los Alamos National Laboratory, has described a novel anhydrous chloride process, used in the nuclear industry to recover plutonium, which could be adapted to extract iron and titanium from nonterrestrial basalts and ilmenite. All reagents and products of the process are recycled and, because it is waterless, the system is one-tenth the size of an aqueous system with the same metal output. It has the disadvantage of being a metal extraction process that does not directly yield oxygen or water, and it requires chloride salts, which are rare or absent on the Moon. However, as a successful operating anhydrous system that recycles all reagents and products, it merits serious consideration for nonterrestrial application.

Karl R. Johansson has reviewed the literature and found several bioprocesses for the beneficiation of lunar and asteroidal materials by the action of microorganisms. Notably, the extraction of metals by (1) oxidation-reduction reactions, (2) acid leaching, (3) pH alteration, (4) organic complexing, and (5) cellular accumulation of metals due to the action of bacteria on minerals. All these bioprocesses would require stringent radiation and temperature controls in closed aqueous environments having elements in which the Moon is deficient, like carbon, nitrogen, and hydrogen. However, Karl says that the process of microbe-enhanced vat leaching, which is used terrestrially to concentrate copper ores, might be applicable to extracting common lunar metals like iron and manganese from lunar rocks and soils. In addition, bioaccumulation of metals by microbial cells might be used to concentrate rare (and often toxic) elements like copper, lead, mercury, cadmium, and silver and remove them from biological systems on the Moon. In his paper Karl also mentions metal reduction by anaerobic bacteria, the uptake of silicates by diatoms, and a tantalizing claim in the Russian literature of "silicate bacteria" that concentrate aluminum oxide by freeing silicates from aluminosilicate ores. However, human settlements and early lunar industrial operations would probably have to be well established before controlled bioprocessing systems could be set up in nonterrestrial locations.

If aqueous processing were to prove practicable, then leaching of useful elements from lunar and asteroidal materials by inorganic acids like hydrofluoric acid, without the introduction of microorganisms, might well be a more direct and productive method of extracting most of the major lunar elements (oxygen, silicon, aluminum, iron, magnesium, titanium) as well as many of the minor ones (sodium, potassium, manganese, chromium, phosphorus). See Criswell (1980).

Metallurgist Constance F. Acton has critically reviewed proposed processes for metal production, using the harsh criterion of terrestrial commercial viability. Iron in lunar soil may be the most easily obtained metal resource on the Moon through the low energy extraction techniques of magnetics and electrostatics. Its physical extraction presents many challenges, but it is likely to be one of the easier objectives for near-term lunar resource development (Agosto 1981). Acton points out the need for hard thermodynamic and kinetic data on all the reactions and the necessity for long-term bench-level testing and pilot plant facilitation of the most promising processes. She outlines the extensive effort required to prove a commercial metallurgy process through thermodynamic and kinetic chemical evaluation, bench-level feasibility studies, and pilot plant operations. Her assessments, based on terrestrial experience, of long lead times (20-50 years) and high R&D expenditures (hundreds of millions of dollars) to develop systems are challenges to the designer of lunar materials processing technology. However, the long lead times presume development of processes competitive with those of terrestrial suppliers. That assumption does not apply to the initial provision of products from lunar sources for use in orbit.

John Lewis, of the University of Arizona, presented to our group information on the gaseous carbonyl process. Carbon monoxide is reacted with metal at low temperature to purify it or separate one metal from another. With a relatively low energy input, lunar metallic iron might be purified or trace elements, particularly platinum group metals, could be separated from asteroidal metal. Although considerable terrestrial experience is in hand, adaptation to the space environment remains a challenge for future investigation.

Nonterrestrial Cements

T. D. Lin, of Construction Technology Laboratories (CTL), the research arm of the Portland Cement Association, proposed to our workshop group the manufacture of cement from lunar oxides and in his paper proposes concrete as a building material for a space station and a lunar base. The major constituents of common types of cement occur in lunar highland anorthosites and lunar mare basalts. The high compressive strength and the mass of lunar-derived concrete would make it an effective shield against radiation and micrometeorite impacts and thus a candidate material for orbital and lunar structures. Concrete is fireproof, lends itself to modular construction, and can be reinforced with Moon-derived metals and fiberglass to improve its tensional and flexural strength. Lunar cement would also be useful as mortar to assemble building blocks of other materials, whether imported or nonterrestrial. Common concrete mixtures are about 10 percent water by weight, but drier formulations can be developed and the water can be recovered as the concrete dries. In any case, typical concretes, which consist of 2/3 to 3/4 aggregate materials bonded by cement, retain only 5 percent water when thoroughly dried, which corresponds to only a few tenths of a percent of Earth-derived mass in the form of hydrogen (Cullingford, Keller, and Higgins 1982). Suitable lunar aggregates could readily be obtained by crushing and grading rocks from the lunar surface.

I have proposed a method for concentrating lime (CaO) in lunar materials to Portland cement formula levels, using phosphates that might be lunar derived. A similar process was proposed by Ellis M. Gartner, of CTL, using terrestrial phosphate. Construction Technology Labs received 40 grams of lunar soil from the Johnson Space Center in 1986; from it CTL fabricated a lunar mortar sample, which was tested and proved usable. NASA is interested and the project has attracted favorable attention from the press. The apparent widespread interest in cement as a lunar product and public recognition of it may generate substantial support for its development.

The consensus of the group working on beneficiation and extraction of nonterrestrial materials was that there is a near-term need for bench-level data on lunar and meteoritic materials processing, such as (1) beneficiation of industrially valuable minerals in lunar soils and disaggregated lunar rocks and meteorites; (2) oxygen and metal extraction processes, like carbothermal reduction of silicates, hydrogen reduction of ilmenite, magma electrolysis, vacuum pyrolysis, and anhydrous chloride reduction, using actual nonterrestrial samples; and (3) formulation of cementitious compounds from lunar oxides and aggregates. The above research should be conducted under conditions approximating, as closely as practicable, the expected operating environment. This work is necessary to make a credible case for nonterrestrial materials utilization to the materials science community.

Recommendations

1. Support for a thorough bench-level hardware investigation and demonstration of the beneficiation, primarily by electrostatic and magnetic means, of lunar soils and crushed rocks for minerals like ilmenite, anorthite, and pyroxenes, and valuable minor phases like metal, chromite, and phosphate.

2. Support for bench-level research and development of the carbothermal process, including additional testing to determine optimum pressure and temperature conditions for feedstocks of various compositions, such as simulated mare basalt and concentrates of ilmenite or pyroxene.

3. Support for a thorough investigation of the thermodynamics and kinetics of hydrogen reduction of lunar ilmenite, together with a bench-level laboratory research project to investigate the workability of hardware designs like those of Richard J. Williams and Christian W. Knudsen and Michael A. Gibson.

4. Support for additional studies of magma electrolysis, including laboratory work on the basic process, development of innovative electrodes and containers, and investigation of the effects of feedstock of different compositions. This effort should also include engineering evaluations and plant design concepts.

5. Support for a thorough investigation of the thermodynamics and kinetics of solar furnace vacuum pyrolysis of nonterrestrial materials. The effort should

include a bench-level research project to characterize, quantify, separate, and capture oxygen and other volatiles liberated by high-temperature vacuum pyrolysis of lunar and meteoritic materials, as well as thorough characterization and chemical analysis of resulting condensates and residues.

6. A literature search and evaluation of the anhydrous chloride process for plutonium reclamation reported by David F. Bowersox and its applicability to production of metals and ceramics from nonterrestrial materials.

7. Support for bench-level research on aqueous leaching of nonterrestrial silicates with inorganic acids like hydrofluoric acid, as well as beneficiation by bioprocesses derived from the action of microorganisms on nonterrestrial minerals.

8. A study of the application of the carbonyl process to the purification and extraction of lunar and asteroidal ferrous metals.

9. Support for the development of cement formulations from lunar materials and cement and concrete fabrication processes adapted to lunar and orbital manufacture and applications.

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Lunar Beneficiation

William N. Agosto

With the exception of igneous differentiation and possible fumarolic activity (volcanic exhalations), the Moon lacks all the major ore-forming processes that operate on Earth—aqueous concentration of crustal minerals, surface weathering of rocks, advanced fractionation of igneous rocks, and plate tectonic recycling of the crust. For that reason, natural concentrations of industrially valuable minerals (ore bodies) are far less likely to be found on the Moon than on the Earth (see James Carter's paper, earlier in this volume). But that is all the more reason for devising beneficiation processes to concentrate and extract the useful mineral components in lunar rocks and soils. Another important consideration is that nearly complete reagent recycling will be required for most of the processes proposed for producing oxygen, metals, and ceramics on the Moon. Reagent recovery will be greatly simplified by using simple input ore minerals. Examples of such minerals are ilmenite, the most abundant lunar oxide and a source of oxygen, iron, and titanium; anorthite, the chief source of lunar aluminum; and metallic iron/nickel fragments that occur in lunar soil. In addition, there may be significant amounts of chromite, sulfides, and phosphates in terranes that are rich in chromium and KREEP (potassium, rare earth elements, and phosphorus).

As an example of a useful mineral that can be beneficiated, McKay and Williams (1979) have estimated ilmenite abundance by microscopic count to be 15 and 20 percent by volume in Apollo 11 and 17 basalts and 2 and 5 percent by volume in Apollo 11 and 17 soils. Reduction of lunar ilmenite with hydrogen imported from Earth appears to be one of the more practical schemes for obtaining lunar oxygen. While the reported concentrations are significant, a more highly concentrated ilmenite extract would improve the efficiency of the reduction process.

Electrostatic Concentration

In 1985, I reported designing mineral electrostatic separators based on commercial models. With my separators, I demonstrated the electrostatic concentration of lunar ilmenite in the 90- to 150-micrometer grain size fraction of Apollo 11 soil 10084,853 to levels above 60 percent at collection points near the high-voltage electrode after one pass through a slide-type electrostatic separator in a nitrogen environment (figs. 1 and 2). Ilmenite behaved like a semiconductor and was separable electrostatically because the other major soil components, including the metal-bearing agglutinates, behaved like nonconductors.

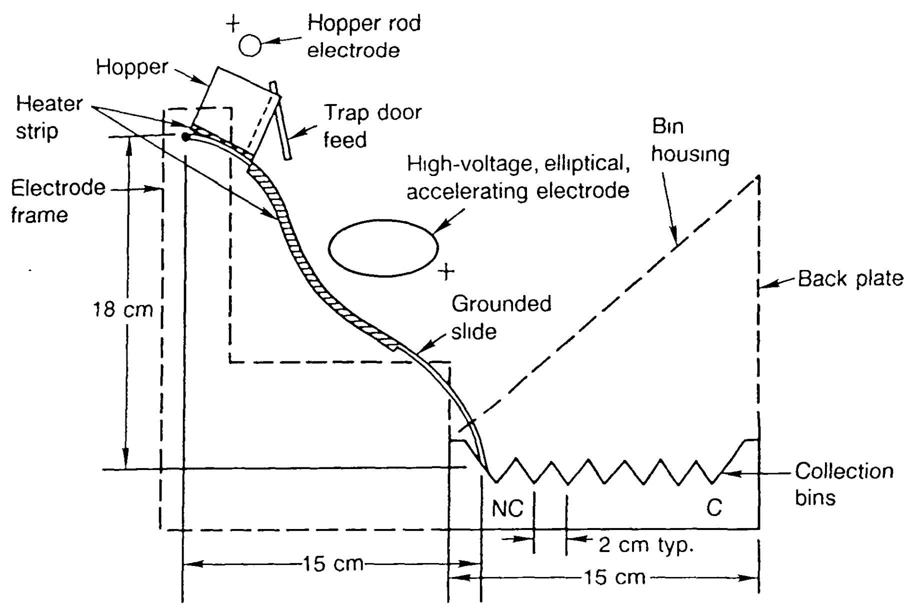

Figure 1

Mineral Electrostatic Separator, Slide Configuration

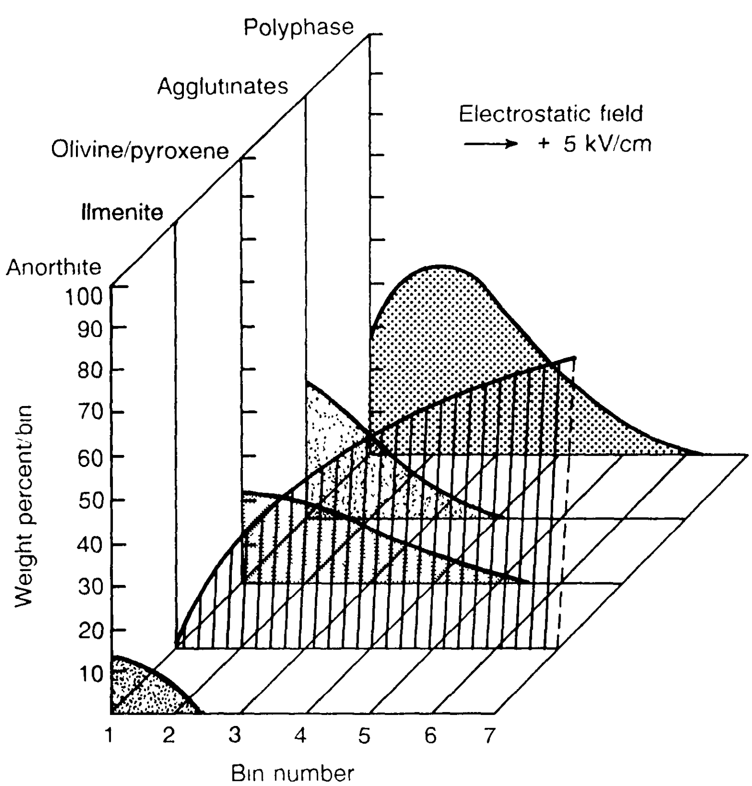

Figure 2

Electrostatic Separation in Nitrogen of Apollo 11 Soil 10084,853, 90-150 µm Fraction

Agglutinates are the major component of lunar soil, making up, on the average, 50 percent of the regolith. Most of the agglutinates contain finely dispersed metallic iron, which gives them a broad magnetic range that overlaps the magnetic susceptibility of other soil components, including ilmenite. For that reason, it is difficult to separate agglutinates from ilmenite by magnetic means. However, the nonconducting behavior of the agglutinates allows them to be separated from ilmenite electrostatically. During separation, the soil sample was heated to approximately 150°C to drive off terrestrial water and enhance the contrast in conductivity between ilmenite and other mineral components (see fig. 3).

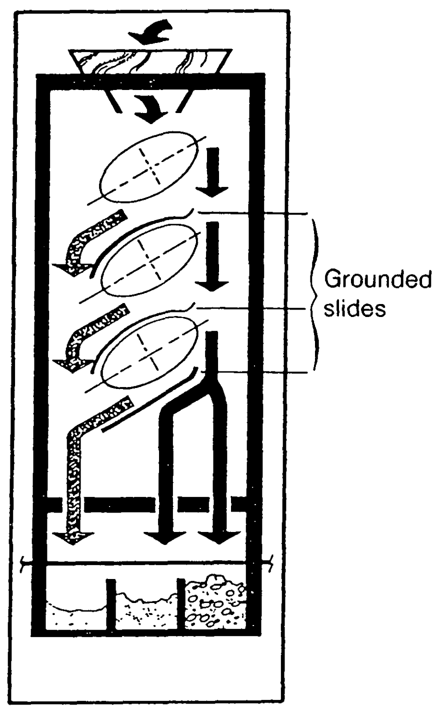

Figure 3

A Commercial Electrostatic Separator on the Lunar Surface

The mirror in this concept of an electrostatic separator on the Moon focuses solar radiation on the soil to be separated. Heating to about 100°C will increase the conductivity of the semiconductor ilmenite while leaving the conductivity of insulators like agglutinates unchanged. The enhanced contrast in conductivity increases the separability of these components of the lunar soil.

In the schematic, the arrows indicate the path of the soil feed and how it separates. The ellipses are cross sections of the high-voltage electrodes. The nonconducting materials fall to the far right. The middlings fall in the middle. The conducting and semiconducting materials fall to the far left.

In my electrostatic studies the lunar anorthite seemed to collect preferentially close to the grounded electrode (the feed hopper), but the slide design of the separator was not configured to take advantage of that.

The slide did enhance the density segregation of ilmenite by air (nitrogen) resistance. Ilmenite is almost twice as dense as the other major soil components. Accordingly, electrostatic separation of the ilmenite in a vacuum, where air resistance was not a factor, was not as successful, and the mineral reached a maximum concentration of only 30 percent in one pass under those conditions (fig. 4). This, however, amounts to a fourfold increase compared to the starting concentration of 7 percent.

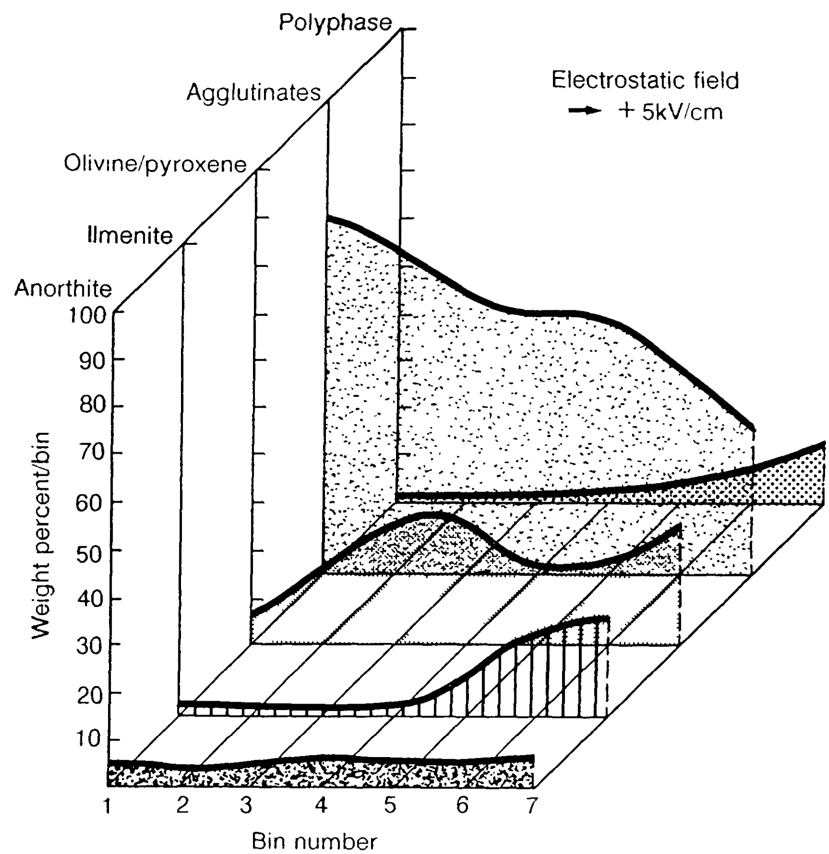

Figure 4

Electrostatic Separation in a Vacuum of Apollo 11 Soil 10084,853, 90-150 µm Fraction

To improve yield in the vacuum of the lunar environment would require redesign of the electrostatic separation apparatus. A vertical, free-fall design (as seen in fig. 3) might be the best approach for separating lunar soil minerals according to their electrical behavior and would be especially appropriate in the lunar environment, where fall times are about twice what they are on Earth.

Magnetic Concentration

Unlike Earth soils, all lunar soils contain naturally occurring, particulate iron/nickel metal (FeNi), which is believed to derive from meteorite impacts. Lunar soil metal is likely to be an accessible and useful resource. Goldstein and his associates (1972, 1973) reported soil metal contents of 0.15 percent by weight in the size range 74 µm to 1.0 mm of three Apollo 16 soils and 0.05 percent by weight in a comparable size range of two Apollo 14 soils. If these occurrences are typical of the lunar highlands and maria, respectively, then there are at least 7 billion metric tons of accessible FeNi metal in the top 10 cm of soil over the entire lunar surface. And there may be substantially higher concentrations of surface metal in regions where iron meteorites have struck the Moon.

In 1981, I proposed a magnetic beneficiation method for concentrating lunar soil metal, using off-the-shelf permanent magnet separators and autogenous grinders. Projected yield was 552 metric tons per year of 99-percent pure FeNi powder. The specific energy required to extract the FeNi metal magnetically was 0.4 kWh/kg, an order of magnitude less than that required to smelt iron from typical ores. A major advantage of the concentrated metal powder product is that it may be formable directly by flexible, low-power powder metallurgical techniques to make a variety of tools, machine parts, plates, struts, wires, electrical contacts, and magnets. Near-theoretical density for these parts may be achievable by powder pressing in the high lunar vacuum. Furthermore, the product can be toughened to steel specifications by adding the right proportions of lunar oxides or titanium to the metal powder before pressing.

An all-magnetic method for beneficiating soil FeNi may present problems because of the large volume of iron-bearing agglutinates that have ferromagnetic properties. But Goldstein did achieve concentration of soil metal grains in the laboratory, using a very low magnetic field gradient on the Frantz Isodynamic Magnetic

Separator, and a comparable technique might be adaptable to industrial operations on the Moon.

I suggest that metal particles first be separated from ilmenite and other soil components magnetically and then, because the ferromagnetic agglutinates may have separated with the metal particles, electrostatic separation could be used to eliminate the agglutinates from the desired metal fraction. Comparable combinations of techniques may be appropriate for extracting other soil components, like anorthite, chromite, and phosphates.

Lunar Soil Sizing

What volatiles are known to exist on the Moon tend to be concentrated in the fine soil fractions. For example, Gibson et al. (1987) showed that hydrogen implanted by the solar wind increases tenfold as particle size decreases—from 12 ppm in the 90- to 150-micrometer fraction to 127 ppm in the less-than-20-micrometer fraction of five representative regolith samples. Overall hydrogen content is about 40 ppm. At 75-percent recovery from the top meter of soil over the entire lunar surface, that is enough hydrogen to make a water lake 10 meters deep and 44 kilometers in diameter. The helium content of the soil is about the same as the hydrogen content. Furthermore, 0.04 percent of the lunar helium is the isotope ^3He, which is much rarer on Earth and which is a potentially important fusion energy fuel (Wittenberg, Santarius, and Kulcinski 1986). Helium-3 may be the only lunar product that can be returned to the Earth at a substantial profit. Accordingly, lunar soil sizing techniques will be vital to extracting rare and precious lunar volatiles. In addition, sized soil input is required to optimize mineral yield by electrostatic and magnetic separation methods.

Dry sizing techniques that may be appropriate to the lunar environment include electrical sizing, screening, and gas elutriation.

Electrical Sizing

In 1984, I measured the trend of increasing charge-to-mass ratio with decreasing grain size in terrestrial analogs of common lunar regolith minerals and subsequently demonstrated electrostatic sizing of terrestrial ilmenite over the particle size range of 500 down to 90 micrometers (figs. 5 and 6). The previous year, Peter Castle, at the University of Ontario, demonstrated ac electrical sizing of conducting spheres in a comparable size range. In both cases, air turbulence limited the smallest separable size to 90 micrometers. Accordingly, electrical sizing in a vacuum is indicated for grading of fines smaller than 90 micrometers.

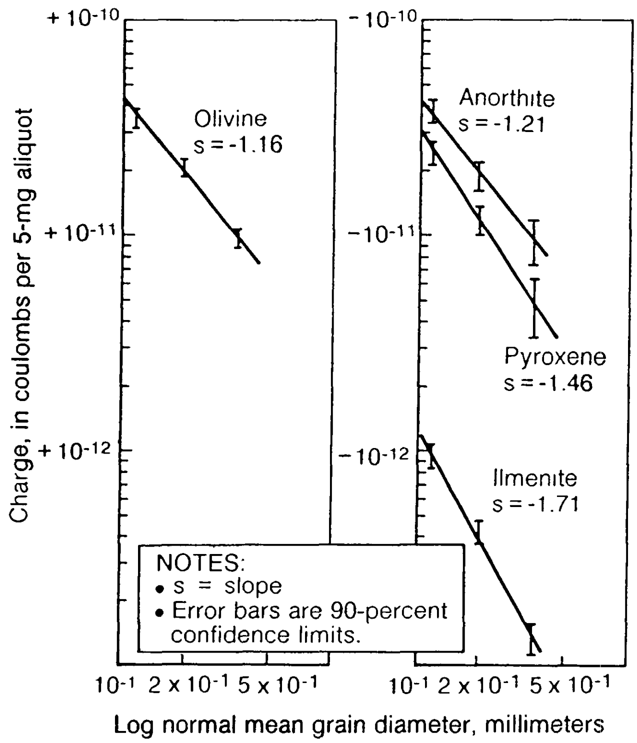

Figure 5

Contact Charge Acquired on Aluminum by Terrestrial Olivine, Anorthite, Pyroxene, and Ilmenite as a Function of Grain Size

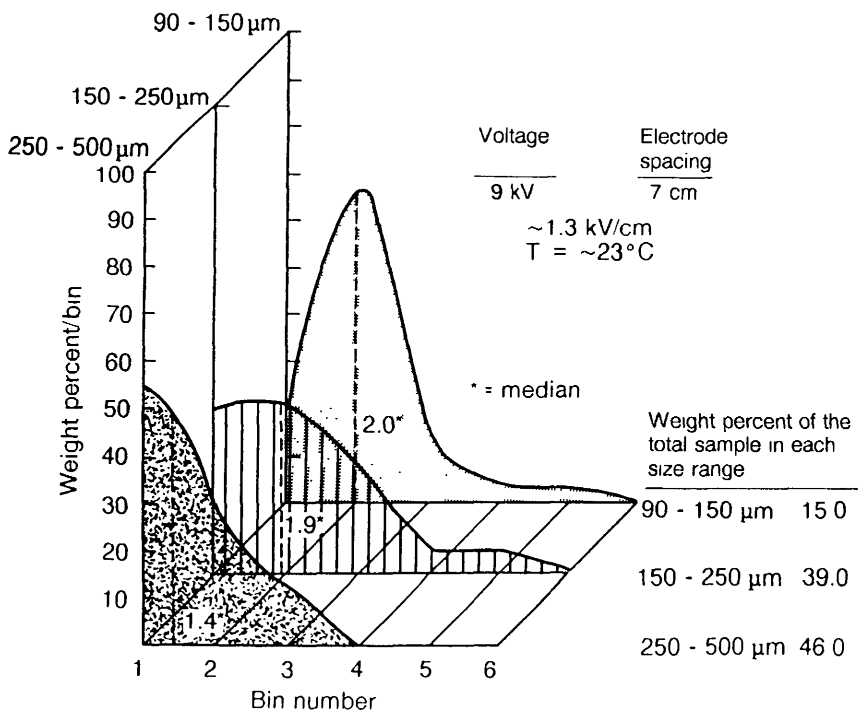

Figure 6

Electrostatic Sizing of Comminuted Ilmenite

Screening

Sieves are available for screening particles ranging from 5 to 30 micrometers at 5-micrometer intervals. It is unlikely, however, that such fine sieving can be accomplished without suspension of the fines in a gas or fluid medium. Even under those conditions, fines sieving is a laborious process. The fluid most likely to be available on the Moon is oxygen, and, since cryogenic temperatures can be relatively easily maintained there, it might be instructive to attempt lunar soil sieving in liquid oxygen. This may be a practical technique because it is unlikely that significant oxidation of lunar soil components will occur at liquid oxygen temperatures (below -183°C). In addition, the only combustible component is FeNi metal, which is less than 1 percent of the soil by weight and which is predominantly encapsulated in glassy agglutinates.

Gas Elutriation and Classification

Gaseous classifiers, cyclones, and fluidized-bed separators operate by stratifying particles in a rapidly moving gas stream according to size and density. They are available on the market for sizing fine particles from 0.5 to 35 micrometers. These devices can deliver the narrowest size ranges (at best, at the small end, a spread of about 0.2 µm) on a commercial scale (kilograms to tons per hour). On the Moon, gas classification might be done in oxygen. The possibility and consequences of oxidizing reduced lunar soil phases under these conditions will have to be considered and experimentally determined. However, it appears unlikely that, by commercial standards, significant oxidation of soil components will occur in dry gaseous oxygen at sufficiently low temperatures (e.g., -20°C) over the short period required for gaseous classification (minutes).

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The Onsite Manufacture of Propellant Oxygen From Lunar Resources

Sanders D. Rosenberg; Robert L. Beegle, Jr.;
Gerald A. Guter; Frederick E. Miller; and Michael Rothenberg

The Aerojet carbothermal process for the manufacture of oxygen from lunar materials has three essential steps: the reduction of silicate with methane to form carbon monoxide and hydrogen, the reduction of carbon monoxide with hydrogen to form methane and water, and the electrolysis of water to form hydrogen and oxygen. The reactions are as follows:

$$MgSiO_3 + 2\,CH_4 \xrightarrow{1625^\circ C} 2\,CO + 4\,H_2 + Si + MgO \quad (1)$$

$$2\,CO + 6\,H_2 \xrightarrow{250^\circ C} 2\,CH_4 + 2\,H_2O \quad (2)$$

$$2\,H_2O \xrightarrow{75^\circ C} 2\,H_2 + O_2 \quad (3)$$

The overall process is shown in figure 7. Figure 8 is a schematic flow diagram of the silicate reduction furnace used in this program.

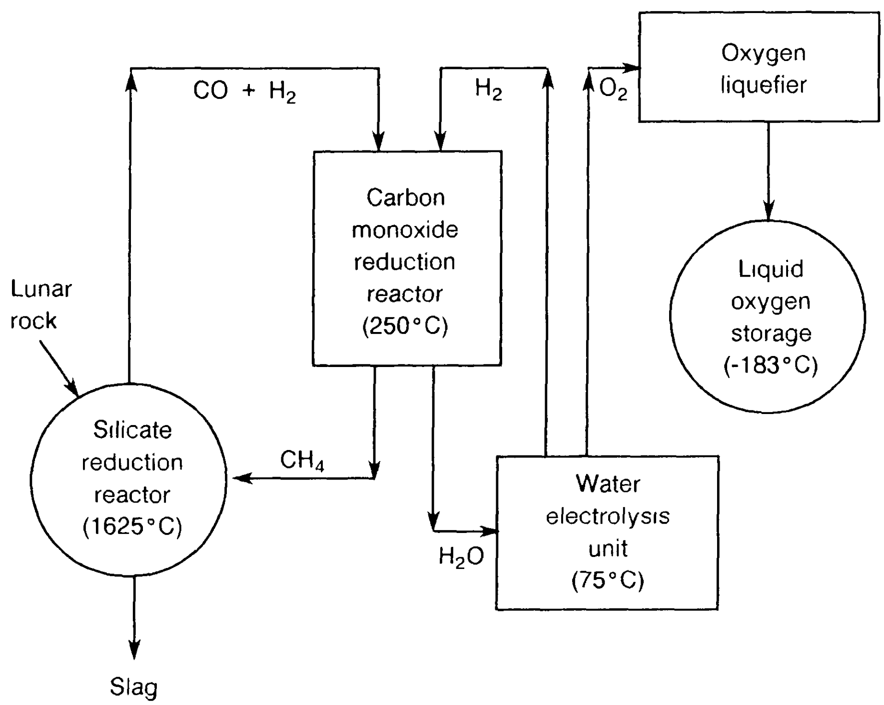


Figure 7

Oxygen From Lunar Silicates

The first of the three steps in the process of carbothermal reduction of silicates takes place in the silicate reduction reactor. Magnesium silicate, which typifies lunar rock, is reduced to carbon monoxide, silicon, and slag, using methane as the reducing agent. The step requires a very high temperature 1625°C

$$MgSiO_3 + 2\,CH_4 \xrightarrow{1625^\circ C} 2\,CO + 4\,H_2 + Si + MgO \quad (1)$$

In the second step, the carbon monoxide is catalytically reduced with hydrogen to regenerate the methane and form water. This step takes place at the relatively low temperature of 250°C.

$$2\,CO + 6\,H_2 \xrightarrow{250^\circ C} 2\,CH_4 + 2\,H_2O \quad (2)$$

In the final step, the water is condensed to a liquid (at 75°C) and electrolyzed to regenerate the hydrogen used in step 2 and to produce the desired oxygen.

$$2\,H_2O \xrightarrow{75^\circ C} 2\,H_2 + O_2 \quad (3)$$

Since the methane and hydrogen are regenerated and recycled, this process ideally uses up only energy and the input metal silicates. Thus, the following reaction can be seen as the sum of the process.

$$MgSiO_3 \longrightarrow O_2 + Si + MgO \quad (4)$$

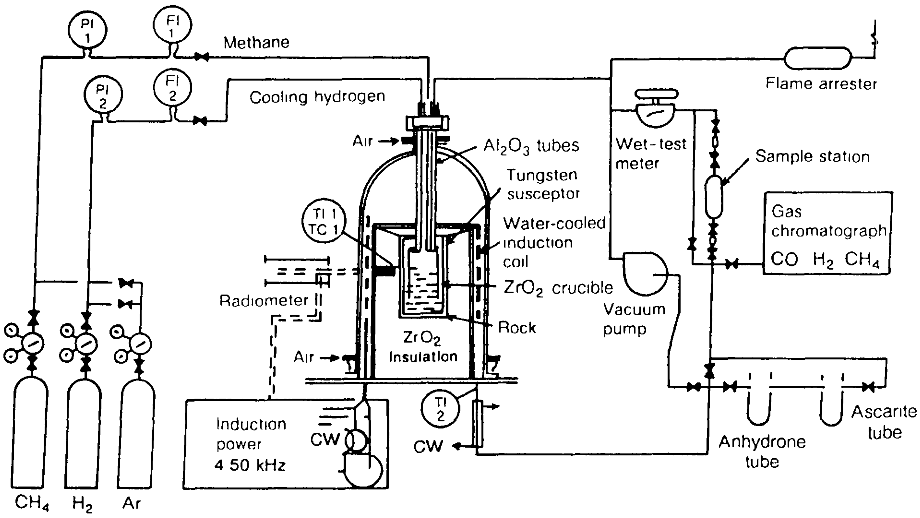


Figure 8

Silicate Reduction Furnace

TI	=	*temperature indicator*
TC	=	*temperature controller*
PI	=	*pressure indicator*
FI	=	*flow indicator*
CW	=	*cold water*

Reduction of Igneous Rock With Carbon and Silicon Carbide

A series of reactions of basalt and granite with carbon and silicon carbide were carried out to determine the temperature profile for the reduction reactions that may occur during the reduction of igneous rock with methane. The results of three of these runs are illustrated in figure 9.

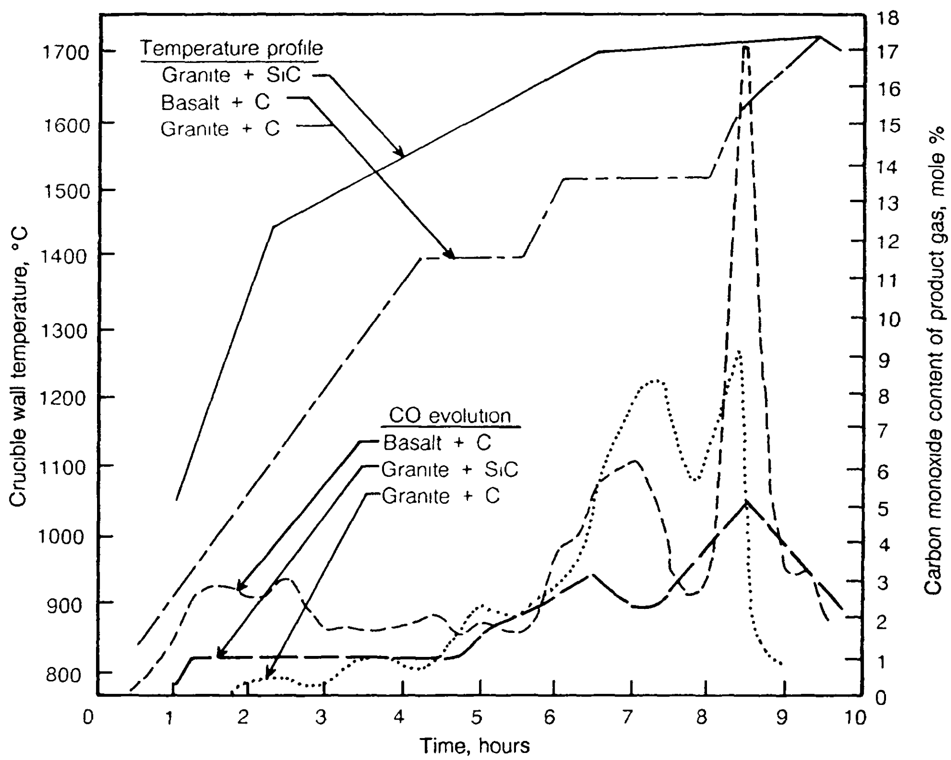


Figure 9

Reduction of Basalt and Granite With Carbon and Silicon Carbide

In the reaction of basalt (50 g) with carbon (5 g), the initial evolution of carbon monoxide resulted from the reduction of iron oxide. The basalt contained 11.86 percent iron oxide (as Fe_2O_3); the reduction of this oxide, if present as Fe_2O_3, would require 1.34 g of carbon. The carbon monoxide that evolved during the first 2.5 hours represented 1.0 g of the carbon. Other reducible materials present in the basalt were titanium dioxide (2.47%) and sodium oxide (3.73%). These oxides would consume 0.43 g of carbon. Consequently, only 35 percent of the carbon could have been oxidized by materials other than silicon dioxide. The recovery in the form of carbon monoxide of 89.1 percent of the carbon with which the reactor was charged indicates that a considerable portion of the silicon dioxide present in the basalt was reduced at temperatures as low as 1550°C.

Three solid products were obtained: slag and metal remained in the zirconium dioxide crucible and sublimate was found at the top of the bell jar. The slag was composed mainly of aluminum oxide. The composition of the metal was 82 percent iron, 13 percent silicon, and minor amounts of titanium, vanadium, nickel, and copper. Of the sublimate, 61 percent was sodium, which is highly volatile.

In the reaction of granite (50 g) with carbon (5 g), much less carbon monoxide was produced at low temperature. This result is due to the lower percentages of reducible oxides in the granite; that is, iron oxide (2.05% as Fe_2O_3), sodium oxide (3.10%), and potassium oxide (4.90%). Complete reduction of these oxides would consume 0.85 g (17%) of the carbon introduced. A total of 73 percent of the carbon introduced was recovered as carbon monoxide; therefore, we conclude that silicon dioxide reduction accounts for most of the carbon monoxide evolved at 1550°C and higher temperatures.

We believe that most of the rest of the carbon introduced reacted with silicon to form silicon carbide. The slag had nonmagnetic pieces of metal dispersed throughout and contained 2.3 percent carbon; that is, 20 percent of the carbon introduced.

In the reaction of granite (37.5 g) with silicon carbide (12.5 g), almost no reaction occurred below 1100°C; about 7 percent of the silicon carbide was reacted between 1100 and 1500°C. As the temperature was increased from 1500 to 1740°C, the reaction rate gradually increased and then rapidly decreased when most of the carbon was consumed. About 83 percent of the carbon in the silicon carbide was recovered as carbon oxides. The dark, metallic looking slag contained an additional 10 percent of the carbon introduced as silicon carbide.

Analysis of the metal recovered from the melt gave 59 percent iron, 28 percent silicon, and minor amounts of titanium, vanadium, nickel, and copper. The slag was composed mainly of aluminum oxide and silicon dioxide.

These results indicate that, if silicon carbide is formed by reaction of granite and carbon, excess granite will react with the carbide to produce silicon and carbon monoxide. The rate of the granite-silicon carbide reaction at 1740°C is comparable to that of the granite-carbon reaction at 1625°C.

Reduction of Carbon Monoxide With Hydrogen

The reduction of carbon monoxide with hydrogen to form methane and water was studied using a nickel-on-kieselguhr catalyst. A schematic flow diagram of the hydrogen-carbon monoxide reactor used in this program is shown in figure 10. The data for these runs are presented in tables 1 to 5 and figures 11 to 13. The various parameters that were studied are discussed in the following paragraphs.

Figure 10

CO-H_2 Reduction Unit

DP	=	*differential pressure transducer*
FCR	=	*flow control recorder*
GC	=	*gas chromatograph*
PC	=	*pressure controller*
PI	=	*pressure indicator (gauge)*
PS	=	*pressure switch*
RV	=	*relief valve*
Ⓢ	=	*gas sample*
🅂	=	*solenoid valves*
ΔT	=	*Δ temperature recorder*
TC	=	*thermocouple*
TI	=	*temperature indicator (thermocouple point)*
WTM	=	*wet-test meter*

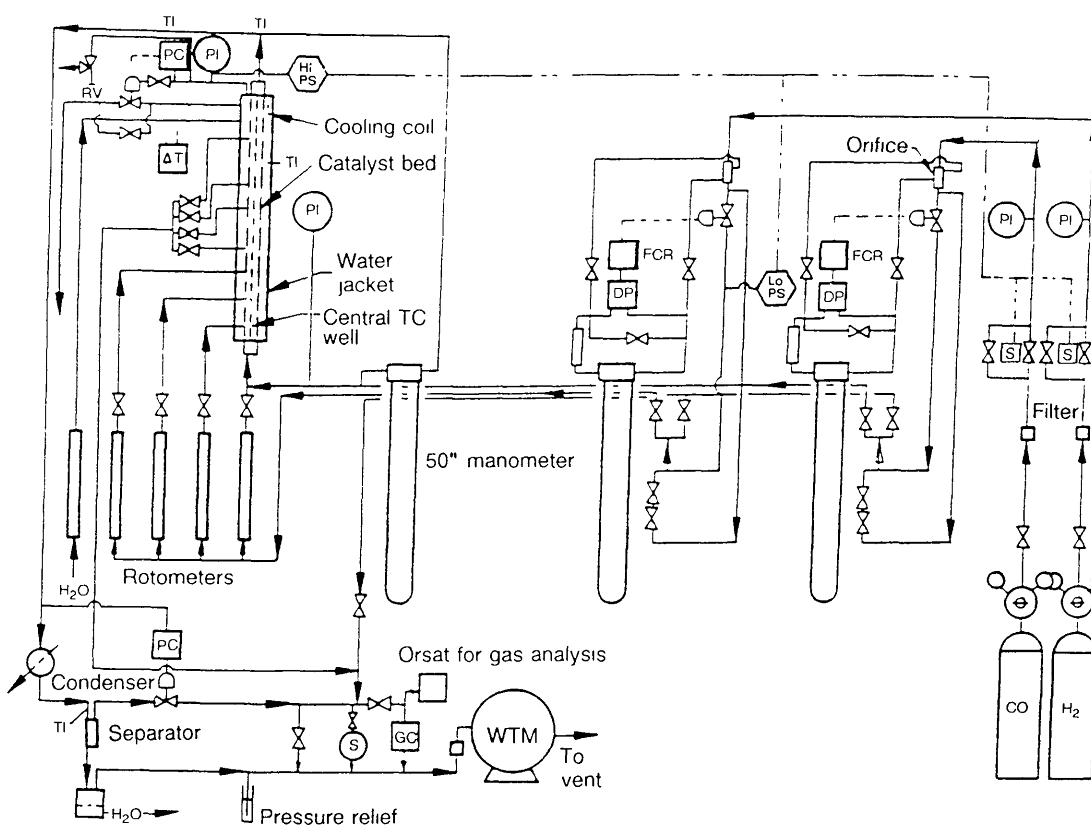


TABLE 1. *Reduction of Carbon Monoxide With Hydrogen To Form Water and Methane (and CO_2): Results of Selected Runs Between 45 and 57*

Run	H_2/CO mole ratio	Space velocity, hr^{-1}	Catalyst bed pressure, atm	Catalyst bed temp., °C	Material balance, %	CO conversion, mole %	Normalized product yield, mole %		
							H_2O	CH_4	CO_2
45	4.00	500	1.0	250	101.0	100.0	100.0	100.0	0.0
46	4.00	750	1.0	249	93 3	100.0	100.0	100.0	0.0
47	4.10	1003	1.0	252	99.0	100.0	100.0	100.0	0.0
48	3.96	1481	1.0	253	95.3	100.0	99.8	99.9	0.1
49a	4.06	1000	1.0	251	101.0	100.0	100.0	100.0	0.0
51	4.15	2010	1.0	265	98.6	100.0	100.0	100.0	0.0
52b	2.84	810	1.0	248	98.1	100.0	91.1	96.2	3.7
53	3.56	1000	1.0	254	94.5	100.0	100.0	100.0	0.0
54	3.14	998	1.0	254	95.0	100.0	98.3	99.1	0.8
55	3.03	1000	6.1	253	96.9	100.0	99.2	99.4	0.4
56	3.01	1500	6.1	231	95.4	100.0	97.3	98.5	1.3
57	3.02	1500	6.1	353	94.8	100.0	94.8	97.1	2.5

TABLE 2. *Analysis of the Gases Produced in the Reduction of Carbon Monoxide With Hydrogen, Selected Runs 45-57*

Run	Composition of product gas, vol. %				
	H_2	H_2O	CO	CH_4	CO_2
45	49.4	1.20	0.0	49.4	0.00
46	49.4	1.15	0.0	49.4	0.00
47	51.5	1.15	0.0	47.3	0.00
48	48.4	1.15	0.0	50.4	0.05
49a	50.8	1.15	0.0	48.1	0.00
51	53.0	1.15	0.0	45.9	0.00
52b	8.9	1.14	0.0	91.5	3.50
53	38.5	1.14	0.0	60.4	0.00
54	17.7	1.14	0.0	80.5	0.65
55	9.3	0.20	0.0	90 2	0.35
56	12.0	0.20	0.0	96.6	1.27
57	18.9	0.20	0.0	78.6	2.25

TABLE 3. *Reactant Gas Carbon Dioxide Content vs. Catalyst Bed Length*

Run	Space velocity, hr^{-1}	H_2/CO mole ratio	CO_2 analysis, vol. %		
			Initial third	Middle third	Outlet
45	500	4.0	0.4	0.0	0 00
46	750	4.0	1.6	0.0	0.00
47	1000	4.1	2.7	0.3	0.00
48	1481	4.0	4.6	0.8	0.05
51	2010	4.1	3.8	0.2	0.00
55	1000	3.0	4.9	1.0	0 35
57	1500	3.0	6.1	3.6	2 25

TABLE 4. *Reduction of Carbon Monoxide With Hydrogen To Form Water and Methane (and CO_2): Results of Selected Runs Between 63 and 67*

Run	Impurity mole % in H_2 stream	H_2/CO mole ratio	Space velocity hr^{-1}	Catalyst bed pressure, atm	Catalyst bed temp., °C	Material balance, %	CO conversion, mole %	Normalized product yield, mole %		
								H_2O	CH_4	CO_2
63b	None	3.00	1000	6.1	254	99.5	100.0	97 6	99.0	0.95
64c	0.1 COS	3.00	1000	6.1	254	97.1	100.0	96.4	98.2	1.65
66b	1.0 NO	2.98	1005	6.1	255	98 8	100 0	98 6	97.2	1.87
66c	1.0 NO	3.44	1120	6.1	252	100.8	100.0	100 0	100.0	0.00
67b	0.5 PH_3	3.09	1024	6.1	249	100.6	100.0	97.2	98.2	1 52

TABLE 5. *Analysis of the Gases Produced in the Reduction of Carbon Monoxide With Hydrogen, Selected Runs 63-67*

Run	Composition of product gas, vol. %						
	H_2	H_2O	CO	CH_4	CO_2	NH_3	N_2
63b	6.0	0.20	0.0	92.9	0.9	----	----
64c	5.0	0.20	0.0	93.2	1.6	----	----
66b	4.0	0.20	0.0	93.3	1.8	0.2	0.5
66c	21.8	0.20	0.0	77.2	0.0	0.3	0.5
67b	10.0	0.20	0.0	88.4	1.4	----	----

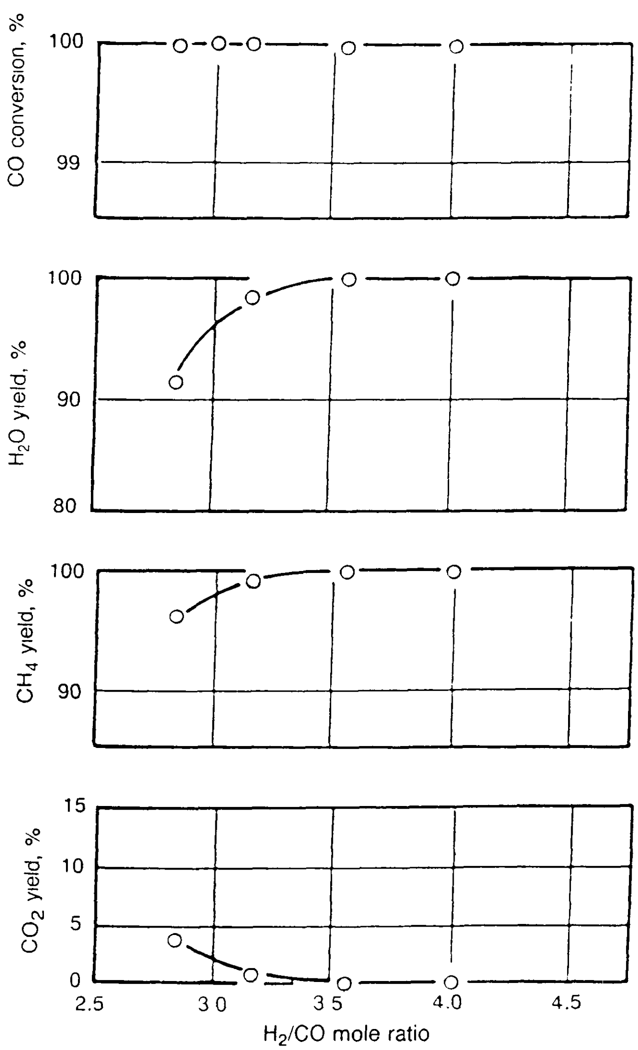


Figure 11

Carbon Monoxide Conversion and Yields vs. Hydrogen-Carbon Monoxide Mole Ratio *(1000 hr^{-1} space velocity; 250°C; 1.0 atm)*

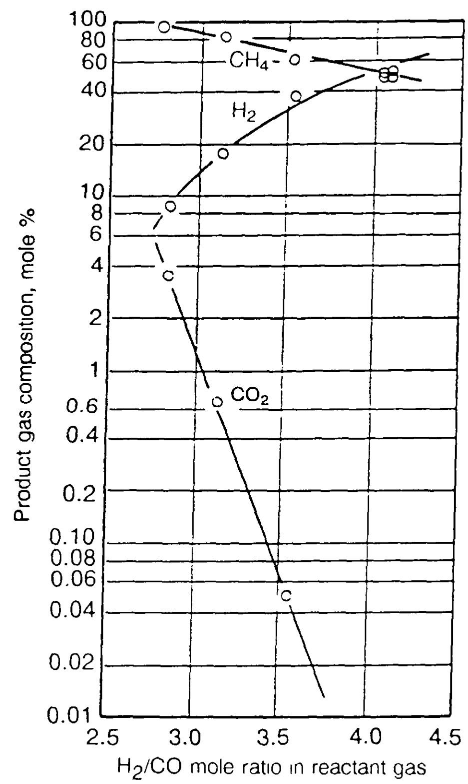


Figure 12

Product Gas Composition vs. Hydrogen-Carbon Monoxide Mole Ratio *(1000 hr^{-1} space velocity; 250°C, 1.0 atm)*

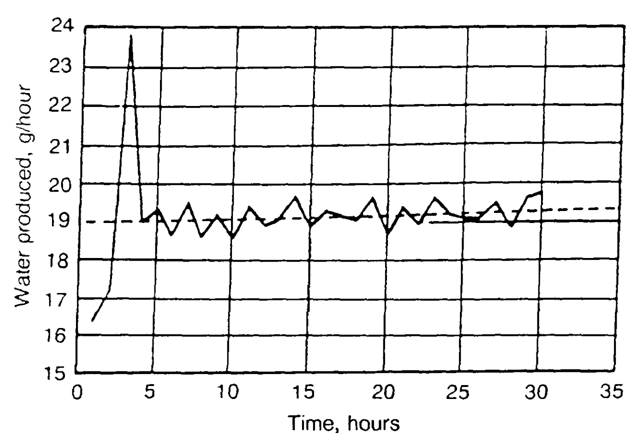


Figure 13

Water Production Rate vs. Time for Run 49 *(1000 hr^{-1} space velocity; 250°C; 1 atm, 4:1 mole ratio)*

Temperature

Some catalyst activity was noted as low as 200°C; the catalyst was found to be very active at 250°C; so excellent conversions were obtained. Therefore, all the runs were made at a nominal catalyst bed temperature of 250°C, except run 57, which was made at 350°C. In run 57 we tried to increase the conversion at a 3:1 hydrogen-carbon monoxide mole ratio and a 1500-hr^{-1} space velocity by increasing the temperature; however, the conversion of carbon dioxide to methane and water decreased as the temperature was increased.

Pressure

The first nine runs were made at atmospheric pressure. The conversions were nearly complete at a 4:1 mole ratio even with space velocities of 2000 hr^{-1}. It was only at lower hydrogen-carbon monoxide mole ratios that the conversions decreased sufficiently to require raising the catalyst bed pressure. The last three runs were made at 6.1 atm to approach complete conversion at a 3:1 ratio. In comparing runs 54 and 55, it can be seen that increasing the pressure from 1 to 6 atm decreased the carbon dioxide yield from 0.8 to 0.4 percent and correspondingly increased the yields of water and methane.

Hydrogen-Carbon Monoxide Mole Ratio

The effect of hydrogen-carbon monoxide mole ratio on conversion and yields can be seen in figure 11. At a space velocity of 1000 hr^{-1}, at 250°C and 1.0 atm, the catalyst gave complete conversion of carbon monoxide and carbon dioxide until we decreased the hydrogen-carbon monoxide mole ratio to less than 3.5:1. The carbon monoxide conversion remained complete but the carbon dioxide yield increased; at a 3:1 ratio, the carbon dioxide yield was approximately 2 percent.

The effect of hydrogen-carbon monoxide mole ratio on the product gas composition can be seen in figure 12. No carbon monoxide could be detected in the outlet gas for any of these runs. Within this range, the carbon dioxide content of the gas increased logarithmically as the hydrogen-carbon monoxide mole ratio was decreased below 3.5:1 (to about 1.5% at 3:1). The theoretical product yield at a 3:1 ratio is 100 percent methane, 0 percent hydrogen. The catalyst gave 86 percent methane, 13 percent hydrogen at the 3:1 ratio.

Space Velocity*

At a 4:1 mole ratio, no carbon dioxide was formed at space velocities up to 2000 hr^{-1}. At a 3:1 ratio, the carbon dioxide yield increased rapidly as the space velocity was increased above 1000 hr^{-1}.

Material Balance

With the exception of two runs, all overall material balances for the runs (see table 1) were under 100 percent. Most of the low material balances can be attributed to low water recoveries. Because the catalyst is known to be a good adsorbent for water, we hypothesized that some of the water was slowly being adsorbed on the catalyst. In order to prove that this was the case, a long-duration run (run 49) was made. See figure 13. The water production, which fluctuated about ± 0.5 g/hr, gradually increased throughout the run (dotted line). After 30 hours, the liquid water production rate was 19.2 g/hr (about 96% of theoretical). At the rate of increase of water production (0.01 g/hr), it would have taken about 100 hr before the actual water production rate equaled the theoretical production rate. For long runs, the water balance should be no problem; in fact, we hypothesize that the small amount of water adsorbed on the catalyst may help to prevent carbon formation.

Heat Balance

In all runs, the majority of the heat was released in the initial third of the bed; however, in several runs at high space velocity (1500 or 2000 hr^{-1}) or low hydrogen-carbon monoxide mole ratios (3:1) or both, enough heat was released in the middle third of the catalyst bed to require some cooling. At the highest space velocities, temperature control was very difficult, because of the large amount of cooling air required to maintain the nominal catalyst bed temperature.

Pressure Drop

The relatively low pressure drop across the catalyst bed was excellent. It did not go up with time even at hydrogen-carbon monoxide mole ratios as low as 3:1. Run 49 was continued for 31 hours without shutdown; the pressure drop did not increase a measurable amount during this long period. The absence of a pressure buildup at the catalyst bed indicated no carbon deposition and a long, useful catalyst life.

* *Space velocity* is a measure of reactor capacity. It is the reciprocal of *space time*, which is defined as the time elapsed in processing one reactor volume of feed at specified conditions. Thus, *space velocity* is the number of reactor volumes of feed that can be processed within a given time. The higher the space velocity the better, provided the desired reaction occurs.

Catalyst Life

The catalyst was still active when it was removed after 14 runs (110 hr). As can be seen from the tabulation below, analyses of the catalyst before and after use showed no carbon deposition.

Time, hr	Carbon content of catalyst C-0765-1001-1, wt. %
0	5.08
110, initial third	5.02
110, middle third	5.11

As stated previously, there was no pressure buildup during the run, so this would not be a limiting factor on the life of the catalyst. However, impurities in the feed may prove to be a limiting factor. Temperature control is also vital, because carbon is definitely deposited on the catalyst at higher temperatures (400°C and up). Catalyst life would probably be extended if the operating temperatures were started low when the catalyst was new and active and then gradually raised as the catalyst activity declined.

Catalyst Bed Length

At low space velocities, only the first inch or two of the catalyst bed was involved in the major portion of the reaction. As the space velocity was increased, more and more of the bed was involved until, at very high space velocities and low hydrogen-carbon monoxide mole ratios (runs 55 and 57), even the full length of the catalyst bed was unable to achieve complete conversion of carbon dioxide into methane and water. This effect is best shown by carbon dioxide gradients in the reactor taken for the various runs, as reported in table 3. Two additional advantages of a long catalyst bed are that it allows a margin of safety as the catalyst ages and becomes less active and that it allows the initial portion of the bed to act as a guard chamber to remove various catalyst poisons.

Lunar Surface Plant Design

Estimates of the weight and power requirements for a lunar surface plant using the Aerojet carbothermal process are given in this section of the paper. In making these estimates, we assumed that no water is present in, or obtainable from, the lunar material. Large differences in weight result when different cooling methods are employed, because of the large amount of waste heat produced.

Heat Rejection

Two different methods of heat rejection were considered in this study:

1. A dual-cycle refrigeration system to "pump" the heat up to a high rejection temperature
2. Direct heat rejection by radiation to space

The first method is based on standard refrigeration principles. It employs *n*-butane as the primary refrigerant, with water as the secondary refrigerant and the medium for transferring heat to a space radiator. Refrigeration is not used in the second method. Instead, we assume that a radiator is able to reject heat directly into 0 K space.

In the estimates for the different sections of the process, power requirements are given for these two different methods of cooling. In the following tables and figures, method 1 indicates the refrigerative technique and method 2 indicates the radiative technique. The details of the two methods are discussed later in this paper.

Reduction of Silicates With Methane

The estimates of heat and power requirements are based on the following changes:

$$MgSiO_{3(s)}\ (100°C) \longrightarrow MgSiO_{3(l)}\ (1627°C) \quad (5)$$
ΔH = 59.62 kcal/mole

$$CH_4\ (500°C) \longrightarrow CH_4\ (1627°C) \quad (6)$$
ΔH = 21.76 kcal/mole

$$H_2\ (500°C) \longrightarrow H_2\ (1627°C) \quad (7)$$
ΔH = 8.50 kcal/mole

$$MgSiO_{3(l)} + CH_4 \longrightarrow 2CO + Si + MgO + 4H_2 \quad (8)$$
ΔH = 200.57 kcal/mole $MgSiO_3$

The process flowsheet for this section is shown in figure 14.

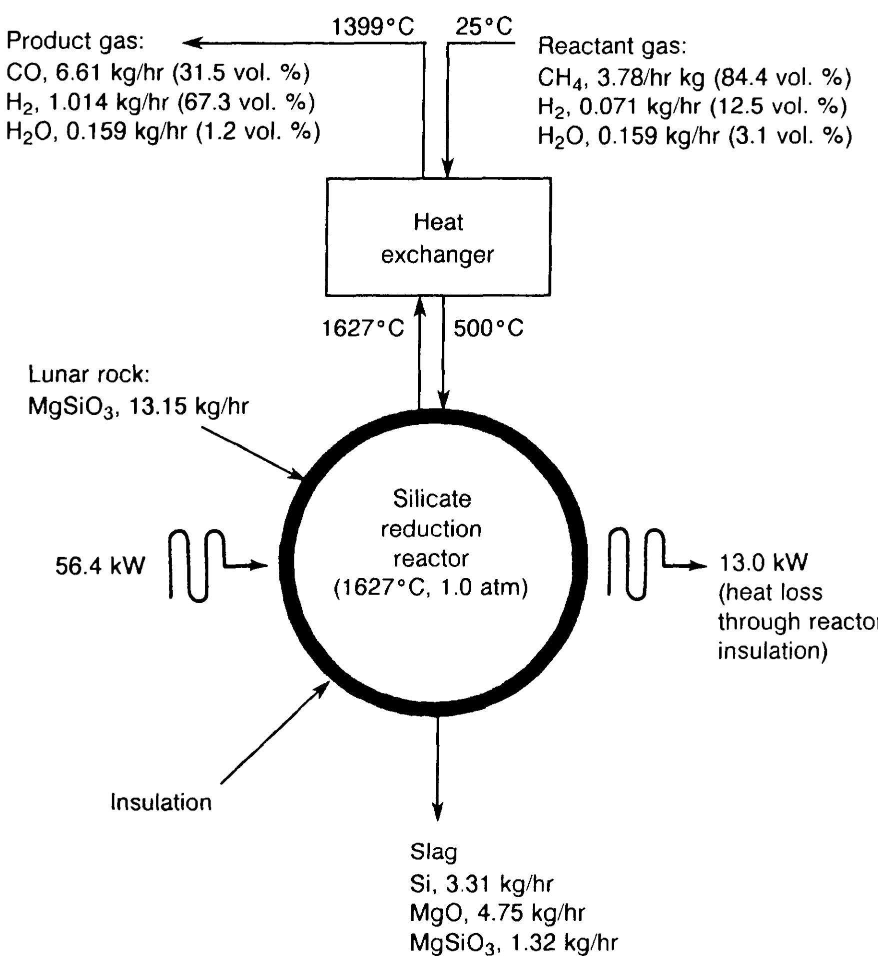


Figure 14

Silicate Reduction Reactor Section

Reduction of Carbon Monoxide

The estimates of heat and power requirements are based on the following changes:

$$CO + 3H_2 \xrightarrow{250°C} CH_4 + H_2O \quad (9)$$
ΔH = -51.61 kcal/mole

$$H_2\,(25°C) \longrightarrow H_2\,(250°C) \quad (10)$$
ΔH = 1.58 kcal/mole

$$CO\,(1399°C) \longrightarrow CO\,(250°C) \quad (11)$$
ΔH = -9.14 kcal/mole

$$H_2\,(1399°C) \longrightarrow H_2\,(250°C) \quad (12)$$
ΔH = -8.42 kcal/mole

$$CH_4\,(250°C) \longrightarrow CH_4\,(25°C) \quad (13)$$
ΔH = -2.25 kcal/mole

$$H_2O\,(250°C)_{(g)} \longrightarrow H_2O\,(25°C)_{(l)} \quad (14)$$
ΔH = -12.35 kcal/mole

The process flowsheet for this section is shown in figure 15. The operating temperature of 250°C is used as a conservative value. Operating at higher temperature offers a modest advantage in reducing radiator weight.

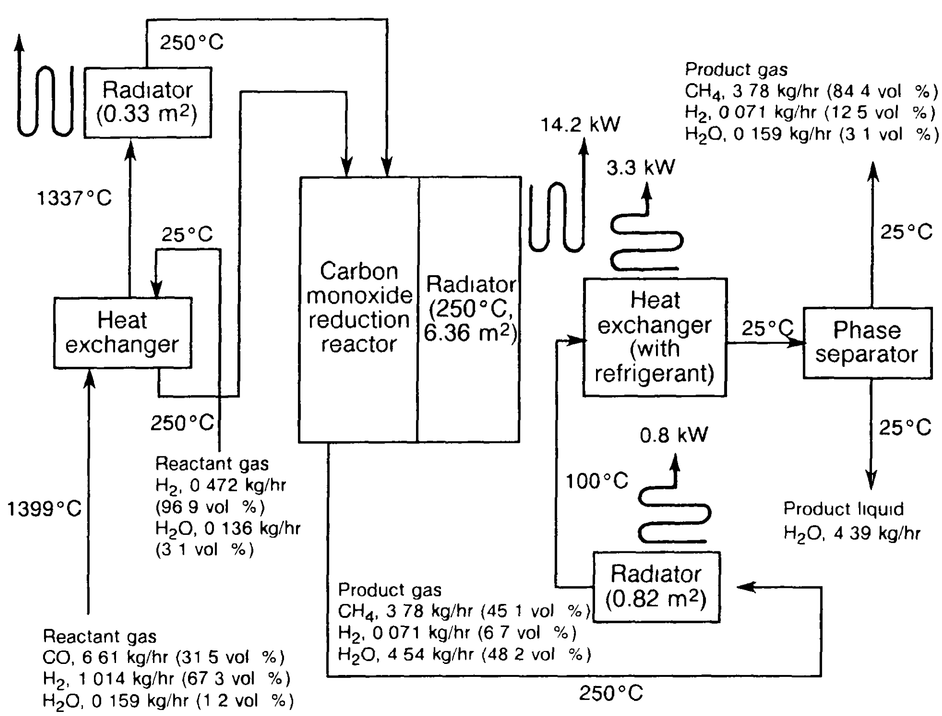
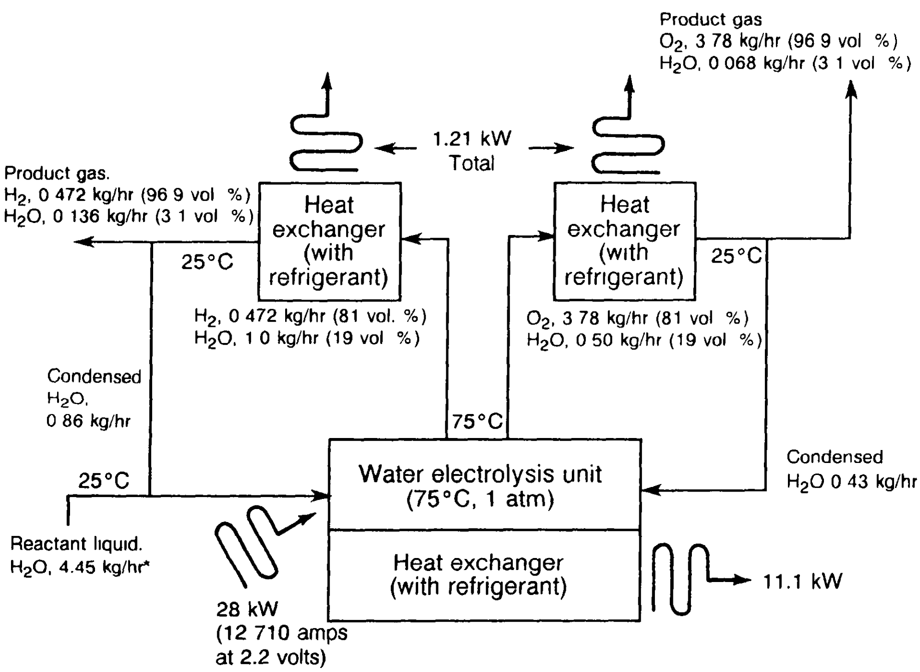


Figure 15

Carbon Monoxide Reduction Section

Water Electrolysis

Most of the weight of the electrolysis unit is that of the refrigeration cooling system and radiators used to reject low-temperature heat. The details of this section are shown in figure 16. A high-pressure electrolysis unit will allow operation at higher temperatures and higher efficiencies—a situation advantageous for both weight and power savings. However, the high-pressure electrolysis unit itself is heavier than a low-pressure unit and, because of added corrosion problems, requires considerably more maintenance. Consequently, detailed tradeoff analysis of low-pressure versus high-pressure electrolysis is needed.



* 4 25 kg/hr required for electrolysis
0.136 kg/hr recycled with hydrogen steam
0.068 kg/hr condensed in liquid oxygen cold trap and returned to electrolysis unit intermittently

Figure 16

Water Electrolysis Section

Oxygen Liquefaction

The oxygen liquefaction system is composed of Norelco type 12080 gas liquefiers. These units use helium as a refrigerant; some makeup helium is required. The details of this section are shown in figure 17. The amount of helium indicated in the tables is for a 1-year operation.

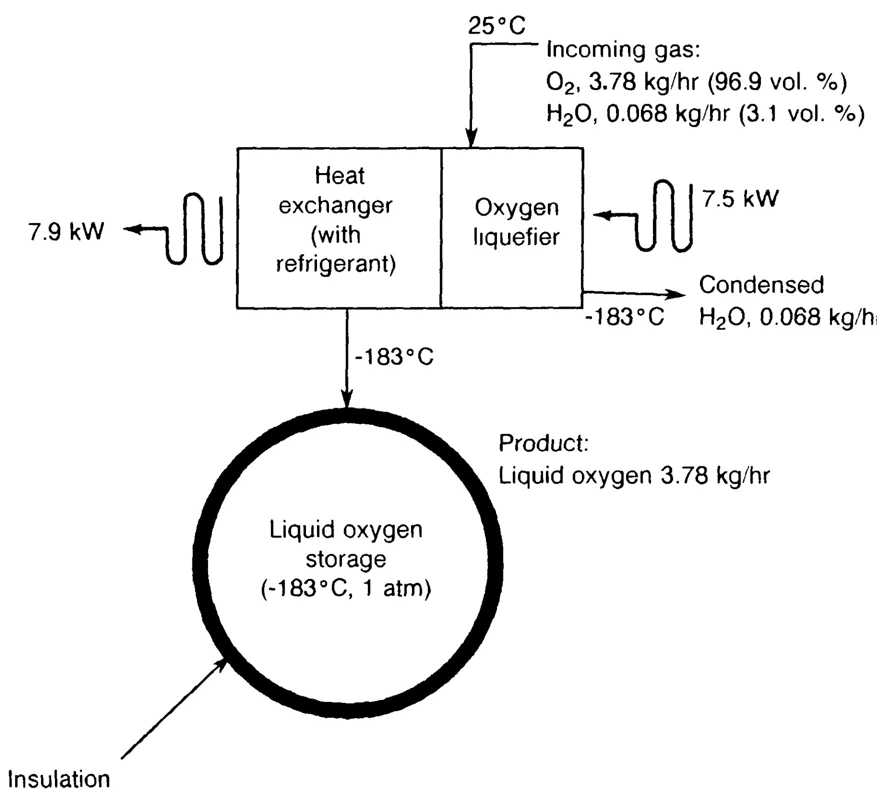


Figure 17

Oxygen Liquefaction and Storage Section

Oxygen Storage

The oxygen storage system consists of spheres of aluminum with walls 1.02 cm thick and an outer diameter of 3.20 m. Each sphere is capable of containing a 6-month supply of oxygen when it is produced at a rate of 2721 kg/month. These spheres are insulated to reduce boiloff. Boiloff oxygen is recondensed and returned to storage. The utilization of empty oxidizer storage tanks on lunar landing vehicles may eliminate the need for these storage spheres. Figure 17 summarizes the details of this section.

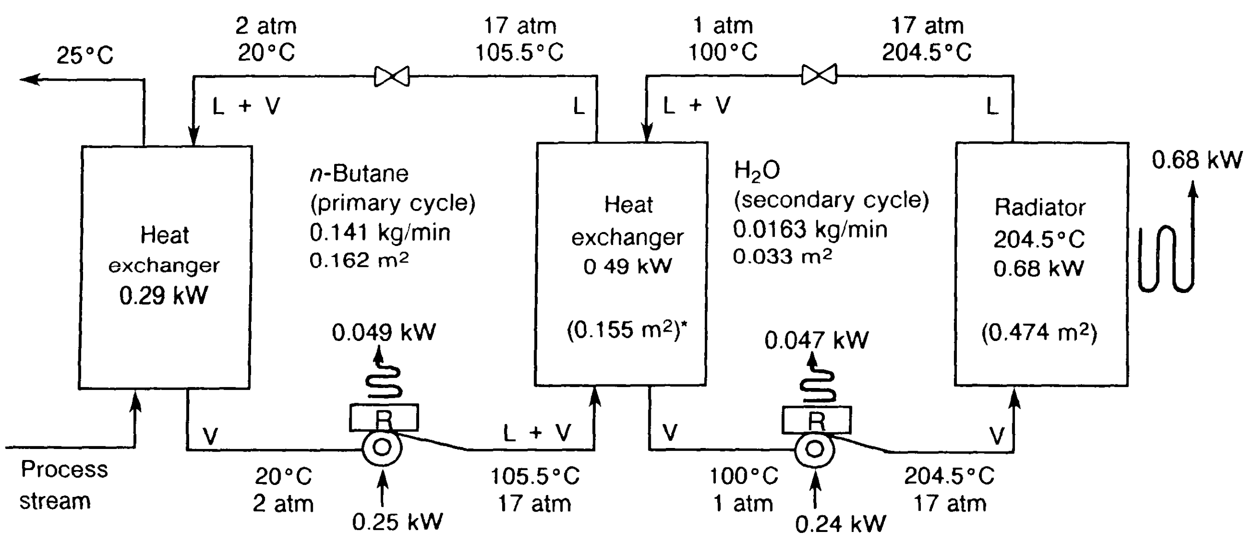
Refrigeration and Heat Radiation

The flowsheet for the refrigeration system used for method 1 cooling is shown in figure 18. The numerical values given are for a heat rejection rate of 0.29 kW. These values may be multiplied by the factor Q/0.29 to obtain correct values for any desired heat rejection rate of Q (kW).

Figure 18

Refrigerative Cooling Method
(Dual Cycle)

[R/O symbol] = *compressor + radiator (compressor efficiency taken as 80%)*
[valve symbol] = *expander*
L = *liquid phase present*
V = *vapor phase present*



* For heat transfer between fluids

The liquid *n*-butane absorbs the heat at 20°C (2 atm), vaporizes, and is compressed to 17 atm (105.5°C). The stream gives up its latent heat to liquid water at 100°C (1 atm) and condenses at 105.5°C (17 atm). Upon flowing through the expander, the *n*-butane partially evaporates until its temperature and pressure are lowered to 20°C (2 atm). It is then returned to the heat exchanger where the cycle is repeated.

The water cycle operates similarly but condenses within the radiator at 204.5°C (17 atm) before it is recycled. The radiator operates continuously at this temperature. We assumed that the radiators would be stationary and lie parallel to the lunar surface, exposed to the full radiation of the overhead Sun (lunar midday)—an extremely conservative assumption.

The radiator material is assumed to have an absorptivity of 0.35 and an emissivity of 0.77. The heat rejection rates for this type of radiator are taken from "Lunar Logistic System" (MSFC 1963). The reported values are based on an estimated 80-percent efficiency. The radiator mass factors used in our estimates were 6.1 kg/m^2 surface area for a plain radiator, and 19.5 kg/m^2 surface area for a radiator with refrigeration. This latter value was also used for systems in which fluids condense or cool in tubes within or attached to the radiator. The 19.5 mass factor was obtained from "Lunar Logistic System" (MSFC 1963).

Compressor efficiencies are taken as 80 percent. The extra power required is rejected as heat from radiators attached to the compressors. Weights of standard compressor and motor units selected for use here were reduced by assuming that nonelectrical parts could be fabricated from lightweight aluminum alloys.

Refrigeration is not needed in method 2. The assumption is made that the radiator sees ~ 0 K space, either by being perpetually shadowed (for example, when located in depressions near the poles) or by being movable so as to present only an edge to the direct rays of the Sun. An iron-clad aluminum radiator would provide an emissivity of about 0.5 in a lightweight body. Reflectors on its underside and edge would prevent pickup of most of the radiation from the Moon's surface and from the Sun. The mass factor is taken as 9.8 kg/m^2 of surface. Once again, an 80-percent efficiency factor was used.

Total System Weight and Power

Table 6 lists the total system weights and power requirements for lunar oxygen plants of three capacities, using method 1 (refrigerative cooling). Table 7 does the same for method 2 (radiative cooling). The differences in weight and power requirements for the two methods are striking, indicating that heat rejection techniques are of major importance in lunar plant design. (See Abe Hertzberg's paper in volume 2, "Thermal Management in Space.") In either case, scaling factors remain about constant.

TABLE 6. *Lunar Oxygen Plant Mass and Power Requirements, Using Refrigerative Cooling (Method 1)*

Section	Plant capacity (kg of O_2/Earth month)		
	2 720	5 440	10 880
Silicate reduction reactor, kg	344	533	943
Carbon monoxide reduction reactor, kg	415	829	1 659
Water electrolysis unit, kg	853	1 688	3 358
Oxygen liquefaction, kg	1 432	2 504	3 577
Refrigeration compressors, kg	445	789	1 406
Subtotal mass, kg	**3 489**	**6 343**	**10 943**
Liquid oxygen storage, kg	1 173	2 345	4 690
Total mass, kg	**4 662**	**8 688**	**15 633**
Silicate reduction reactor, kW	57.5	107.3	204 4
Water electrolysis unit, kW	28.0	56.0	112 0
Oxygen liquefaction, kW	7.5	15.0	22.5
Refrigeration compressors, kW	38.4	76.8	140.9
Total power, kW	**131.4**	**255.1**	**479.8**

TABLE 7. *Lunar Oxygen Plant Mass and Power Requirements, Using Radiative Cooling (Method 2)*

Section	Plant capacity (kg of O_2/Earth month)		
	2 720	5 440	10 880
Silicate reduction reactor, kg	344	533	943
Carbon monoxide reduction reactor, kg	278	555	1 110
Water electrolysis unit, kg	435	854	1 691
Oxygen liquefaction, kg	1 327	2 293	3 261
Subtotal mass, kg	**2 384**	**4 235**	**7 005**
Liquid oxygen storage, kg	1 173	2 345	4 690
Total mass, kg	**3 557**	**6 580**	**11 695**
Silicate reduction reactor, kW	57.5	107.3	204.4
Water electrolysis unit, kW	28.0	56.0	112.0
Oxygen liquefaction, kW	7.5	15.0	22.5
Total power, kW	**93.0**	**178.3**	**338.9**

This study indicates that a lunar plant employing the Aerojet carbothermal process to produce 2720 kg of oxygen per month would have a mass of approximately 4660 kg and require 132 kW_e using refrigeration cooling; a similar plant using radiative cooling exclusively would have a mass of approximately 3561 kg and require 93 kW_e. All estimates are based on a conservative approach to the problem.

Labor Estimates

We estimate that it will take no more than 8 hours' work to operate and maintain any of the three plants under study for 24 hours. One month of plant operation will require 240 work-hours. Based on a cost of $500 000/work-hour, the labor cost for the manufacture of 1 kg of oxygen using the 2 720-kg, 5 440-kg, and 10 880-kg capacity plants is $44 000, $22 000, and $11 000, respectively (1989 dollars).

Cost Comparisons

The dollar costs for the manufacture of oxygen on the Moon can be compared with the cost of delivering oxygen from the Earth by using a labor cost of \$500 000/work-hour and a transport cost of \$54 000/kg of payload. This cost comparison is given in table 8. The manufacture of 2720 kg of oxygen per month for 1 year would cost \$1.71 billion (method 1, most conservative estimate), while the transport of an equivalent amount of oxygen would cost \$1.80 billion.

TABLE 8. *Cost* Comparison: Lunar Oxygen Manufacture Versus Earth-Moon Oxygen Transport (1-Year Cost Savings)*

Plant capacity, kg O_2/Earth month	2 720	5 440	10 880
Kilograms of O_2 per year	32 640	65 280	130 560
\$Cost of delivered O_2 [a]	1 770 x 10^6	3 536 x 10^6	7 079 x 10^6
\$Cost of plant delivery [a,c]	251 x 10^6	472 x 10^6	846 x 10^6
\$Cost of labor [b]	1 430 x 10^6	1 430 x 10^6	1 430 x 10^6
\$Saved by lunar O_2 plant [c]	88 x 10^6	1 637 x 10^6	4 803 x 10^6
\$Saved by lighter lunar O_2 plant [d]	147 x 10^6	1 750 x 10^6	5 088 x 10^6

*Original 1965 dollars have been converted to 1989 dollars using the NASA R&D inflation factor of 4 916 (~5)

[a]Delivery cost of \$54 000/kg

[b]Labor cost of \$500 000/work-hour for 1/3 year

[c]Refrigerative cooling, method 1

[d]Radiative cooling, method 2

The cost of storing oxygen on the Moon is included in the cost of manufactured oxygen but not in the cost of transported oxygen. Utilizing propellant tanks from lunar landing vehicles to store oxygen on the Moon would reduce the cost of manufactured oxygen but not affect the cost of transported oxygen. If the storage cost were not included, the cost difference would be greater.

The data reported in table 8 dramatically indicate that much greater dollar savings will be realized by the manufacture of propellant oxygen on the Moon as the oxygen requirements are increased above 2720 kg/month.

Conclusion

We have shown with laboratory experimentation that the Aerojet carbothermal process is feasible. Natural silicates can be reduced with carbon or methane (see Rosenberg et al. 1965c for methane results). The important products are carbon monoxide, metal, and slag. The carbon monoxide can be completely reduced to form methane and water. The water can be electrolyzed to produce hydrogen and oxygen. A preliminary engineering study shows that the operation of plants using this process for the manufacture of propellant oxygen has a large economic advantage when the cost of the plant and its operation is compared to the cost of delivering oxygen from Earth.

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Processing Lunar Soils for Oxygen and Other Materials

Christian W. Knudsen and Michael A. Gibson

Two types of lunar materials are excellent candidates for lunar oxygen production: ilmenite, $FeTiO_3$, and silicates such as anorthite, $CaAl_2Si_2O_8$ (Kesterke 1971, Williams et al. 1979, Williams and Erstfeld 1979, Steurer 1982, Carroll 1983). Both are lunar surface minable, occurring in soils, breccias, and basalts. Because silicates are considerably more abundant than ilmenite, they may be preferred as source materials. Depending on the processing method chosen for oxygen production and the feedstock material, various useful metals and bulk materials can be produced as byproducts. Available processing techniques include hydrogen reduction of ilmenite and electrochemical and chemical reductions of silicates (Williams and Jadwick 1980, Williams 1985). Processes in these categories are generally in preliminary development stages and need significant R&D support to carry them to practical deployment, particularly as a lunar-based operation.

The goal of beginning lunar processing operations by 2010 requires that planning and R&D emphasize the simplest processing schemes. However, more complex schemes that now appear to present difficult technical challenges may offer more valuable metal byproducts later. While they require more time and effort to perfect, the more complex or difficult schemes may provide important processing and product improvements with which to extend and elaborate the initial lunar processing facilities. A balanced R&D program should take this into account.

Ilmenite—Semicontinuous Process

Primary hydrogen reduction of ilmenite is possible in a relatively clean reaction utilizing one-third of the contained oxygen (Williams and Erstfeld 1979):

$$FeTiO_3 + H_2 \longleftrightarrow Fe^0 + TiO_2 + H_2O$$

Hydrogen would be imported from Earth and the resultant water would be electrolyzed to produce oxygen and recycle the hydrogen. If there are gaseous losses, hydrogen is perhaps the easiest material to make up since it must be transported from Earth for propulsion use.

The biggest limitation to this process is the low equilibrium conversion of this reaction. Relatively small water vapor pressures will stop the reduction and cause it to reverse. One way to enhance conversion has been proposed by Williams (1985). It involves using heat removal to reduce the water partial pressure by condensation in a cold trap, with the water partial pressure limited to its vapor pressure at trap temperature. As water is formed in the reactor, a water vapor pressure gradient is established, and water vapor diffuses from reactor to cold trap and condenses. If diffusion and heat removal rates are fast enough in relation to the water formation rate, the reactor water vapor pressure can be held lower than its equilibrium value at reactor temperature and this lower vapor pressure leads to a higher hydrogen conversion for a given reactor temperature. Oxygen would then be produced and hydrogen regenerated by electrolyzing the liquid water. Diffusion calculations indicate, however, that the vapor pressure cannot be lowered in a system with large enough dimensions to be practical.

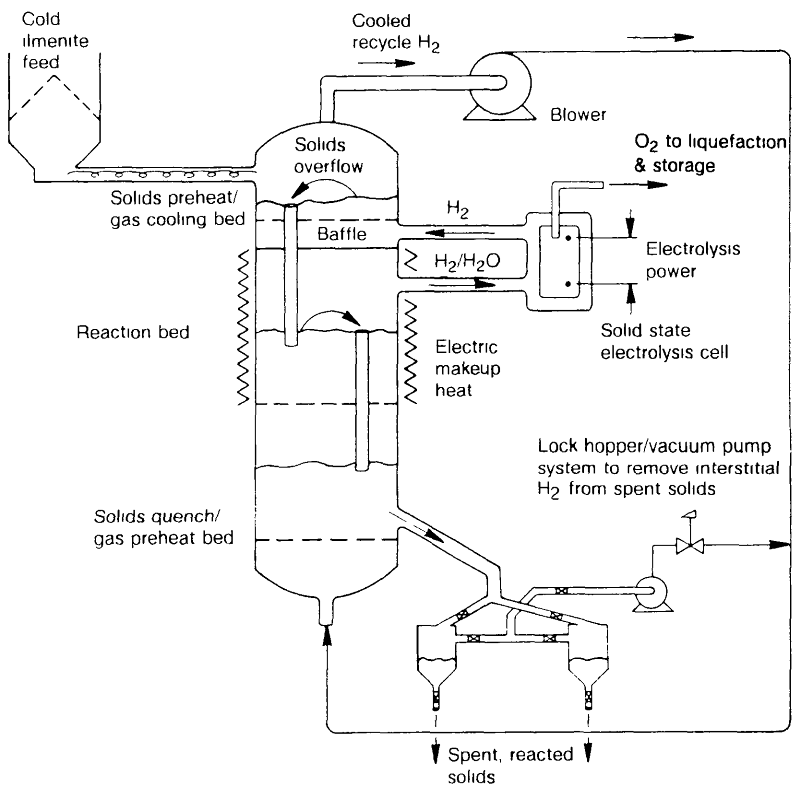
Ilmenite—Continuous Fluid-Bed Reduction

Given the same ilmenite reduction reaction carried out in a reactor with continuous feeding of fresh ilmenite, withdrawal of spent ilmenite, and recirculation of hydrogen gas as both the fluidizing and the reducing medium, a continuous system can be conceived (see fig. 19) if a suitable high-temperature electrolyte can be found to continuously electrolyze the water vapor formed. Zirconium oxide stabilized with either calcium oxide or yttrium oxide appears to be a suitable electrolyte (Weissbart and Ruka 1962, Smith 1966). The high heat-transfer coefficients expected in this process between the gas and the fluidized solids would reduce the necessary size of the equipment. However, this scheme requires the retention of fine reactor solids and high-pressure hydrogen gas and the use of rotating machinery to circulate the hydrogen and to feed the solids. These requirements lead to operational complexities.

Figure 19

Oxygen From Lunar Ilmenite

In this concept for a lunar oxygen plant, ilmenite ($FeTiO_3$) is concentrated from lunar regolith and then fed into a three-stage fluidized bed. In the upper stage, the ilmenite concentrate is preheated by hot hydrogen passing through the powdered ilmenite. The hot ilmenite then goes into the second stage, which is the main reactor bed. Here, even hotter hydrogen reacts with the ilmenite, extracting one oxygen atom from each ilmenite molecule, forming H_2O, metallic iron (Fe), and TiO_2. The H_2O and excess hydrogen are extracted and circulated through an electrolyzer, which breaks down the H_2O. The released oxygen is then cooled, compressed, and stored as liquefied oxygen. The spent feedstock enters the third stage, where heat is extracted by hydrogen gas before the spent material is dumped from the reactor.



NOTE: Cyclones and possibly other gas-solids separators are also required but not shown.

Utilization of Spent Ilmenite To Produce Bulk Materials

The hot, partially reduced ilmenite exiting the direct-reduction reactor might be pressed into blocks or bricks for use in structures or shielding. Further heating may be necessary in the pressing operation. Evidence of successful hot pressing of brick-making shales and fireclays (Crayton and Brownell 1974) and of ashes from the combustion of coal mine wastes (Gartner 1979) into structurally strong blocks or bricks indicates that this utilization of spent ilmenite should be investigated.

Silicates—Electrochemical Reduction

In the case of silicates, hydrogen reduction is not thermodynamically favorable and proposed processing steps include direct electrochemical reduction, reduction with carbon plus chlorine, reduction with aluminum, and reduction with methane (Kesterke 1971; Carroll 1983; Colson and Haskin, immediately following; Williams and Erstfeld 1979; Anthony et al. 1988; Rosenberg et al., immediately preceding).

Kesterke studied direct electrochemical reduction to extract elemental oxygen from silicate-bearing melts experimentally. He used an iridium anode and LiF/BaF_2 fluxing agents in a molten electrolyte/silicate bath at 1050 to 1250°C. Molecular oxygen was produced directly at the anode, but Kesterke found that fuming led to loss of volatile LiF from the electrolyte cell. More importantly, Kesterke concluded that the recovery of the fluoride fluxing agents from the spent electrolyte bath was prohibitively complex. Given experimental observation that SiO_2, the major oxide constituent of Kesterke's melt, experienced little electroreduction, we conclude that large quantities of flux would have to be supplied from Earth or suitable substitutes found on the Moon near the facility.

In all of Kesterke's experiments, a solid deposit of varying size accumulated on the cathode. In this deposit, iron, aluminum, sodium, silicon, and barium were major constituents; manganese, titanium, calcium, molybdenum, and boron were present in significant quantities (the boron and molybdenum probably came from the experimental apparatus); and nickel, zirconium, copper, and chromium were present in lesser amounts. Iron would probably be the first metal produced from a lunar melt since it is the first major product of sequential electrolysis. Further electrolysis of the iron-free melt might yield other metals when processes are perfected.

Further work (including Carroll 1983) suggests that electrolysis techniques may be developed without fluxing materials and with a nonconsumable anode for oxygen production (see the paper immediately following by Colson and Haskin). Preliminary experiments indicate that molten rock or soil is conductive enough to support electrolysis.

Lunar application of electrolysis would yield oxygen directly as well as a number of important metals. Considerable improvement of electrode and containment materials are needed, as are lunar-derived fluxing materials for processes requiring a flux. Ultimately, development of a continuous or semicontinuous process would be desirable to provide uniform product quality and significant production rates.

Silicates—Chemical Reduction

The carbon-plus-chlorine silicate reduction process has several technical difficulties, as outlined in Williams and Erstfeld's thermodynamic study (1979). First, there are uncertainties about the numerous possible products of a high-temperature reaction of chlorine with complex silicates and carbon and about the ability to regenerate the chlorine and carbon quantitatively. Second, the oxygen must be extracted by high-temperature electrolysis of a CO/CO_2 mixture, which will deposit carbon that will probably be hard to remove continuously. Finally, a solid electrolyte of stabilized zirconium oxide (the probable choice for the CO/CO_2 electrolysis) is likely to be corroded severely to $ZrCl_4$ when in contact with hot, chlorine-bearing gases.

More recently (1988), Anthony and colleagues have developed a process that uses aluminum metal to reduce silicon in an anorthite-rich melt containing a flux (see fig. 20). The aluminum oxide is decomposed by electrolysis, producing oxygen and metallic aluminum, which is then recycled. Because anorthite contains abundant aluminum, excess aluminum is produced by the process and can be recovered either as a metal or as an alloy with silicon. Calcium or calcium oxide is subsequently removed from the melt, so the flux can be recycled.

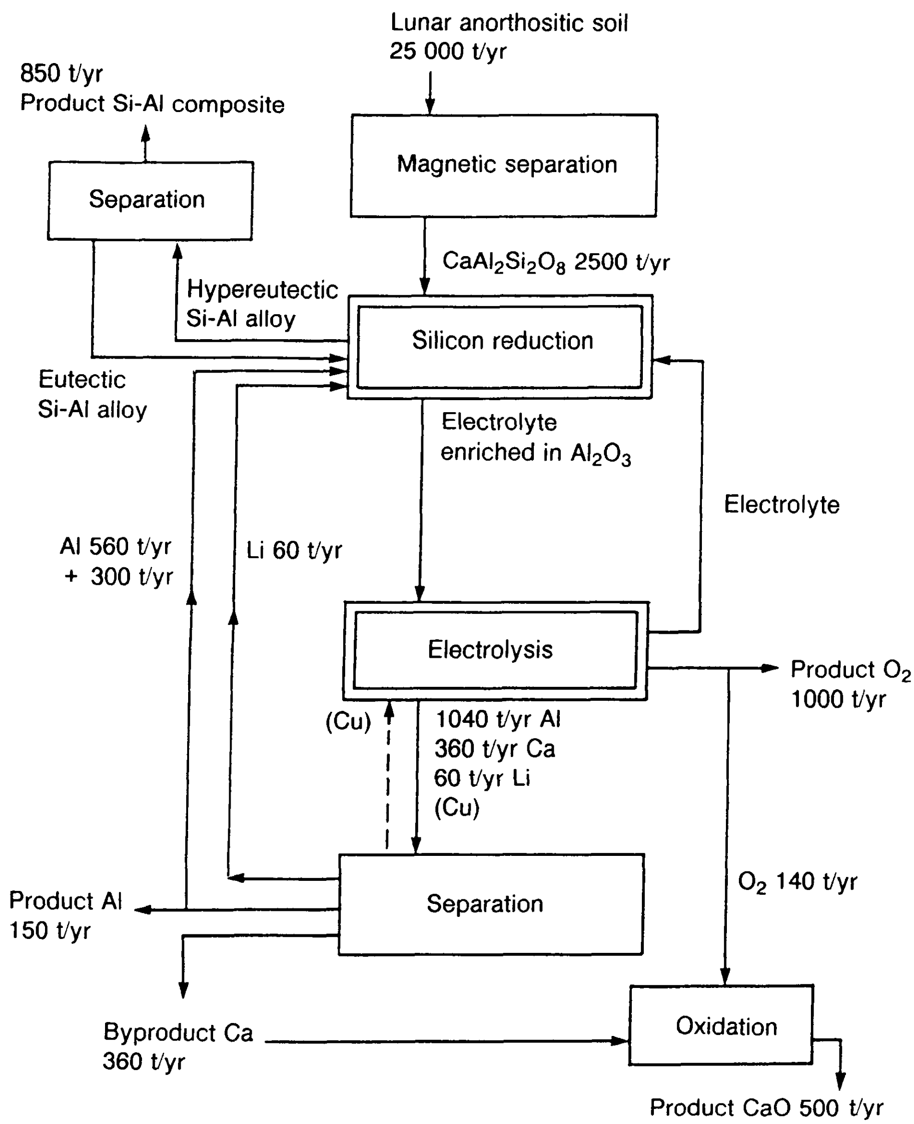


Figure 20

EMEC Process To Produce Oxygen and Byproducts From Lunar Anorthositic Soil

This plant, conceived by EMEC Consultants, is scaled to produce 1000 metric tons of oxygen per year. As byproducts, such a plant will also produce a silicon-aluminum alloy (suitable for casting into structural beams), pure aluminum, and calcium oxide (suitable for use in cement).

The process uses aluminum metal to reduce the plentiful silicon in the mineral anorthite, the most abundant mineral on the Moon. The aluminum oxide is subsequently separated into aluminum and oxygen by electrolysis. Some of the aluminum is recycled to produce more silicon, and some can be used for construction purposes. The calcium from the anorthite can be separated and reoxidized to form an important constituent of cement.

The EMEC process has the advantage that it can produce elemental silicon, elemental aluminum, and casting alloys of silicon and aluminum with low melting temperatures. Also, it can use most of the soil or rock as feedstock, if appropriate highland sites are chosen. This process has the disadvantage that it does require some feedstock beneficiation to eliminate most of the iron-rich minerals. Other disadvantages are that it must have inert electrodes that will not dissolve in the molten flux and it involves a somewhat complex step to recover the flux from the calcium oxide or calcium metal. However, the process is still attractive and the technology can borrow heavily from the existing aluminum-producing industry.

Carbothermal or methane reduction is another process that appears to have potential. It is proposed to operate at approximately 1625°C on molten silicates (Rosenberg et al., immediately preceding; see also NASA handout 1972). This process has the advantage of utilizing the whole soil, not just a beneficiated portion; thus, it requires the processing of a smaller amount of lunar soil. It does introduce corrosion problems. But perhaps the biggest challenge is the complexity and large heat exchange surface required because the methane must be regenerated at about 250°C by hydrogen reduction of carbon monoxide. Exothermic heat from this lower temperature step cannot be used to drive the primary reduction, which proceeds only at much higher temperatures. Nevertheless, methane reduction is clearly a viable candidate among the various chemical reduction processes proposed for silicates, especially if a use for lower level heat is available.

Summary

Of the processes discussed, ilmenite reduction appears to offer the most straightforward chemistry, the lowest operating temperature, the least materials problems, and the easiest to replicate working fluid. Its development needs to be pursued, but other processes need to be advanced simultaneously to develop a variety of processing routes and product possibilities.

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Oxygen From the Lunar Soil by Molten Silicate Electrolysis

Russell O. Colson and Larry A. Haskin*

Introduction

In 1835, a lunar fantasy published as a factual account in the New York *Sun* (see French 1977) generated great economic interest in the Moon. This fantasy reported, among other things, the existence of huge gems on the Moon. Within a few weeks the story was shown to be a hoax, but the interest it generated remained. Now, the Apollo missions have dimmed hopes that such traditional treasures will be found on the Moon. These missions provided no evidence that the Moon ever experienced the plate tectonic processes or the major water and gas transport processes which have produced most gem minerals and ore deposits on Earth. Even if gem minerals and ore deposits had formed, they would probably have been destroyed or dispersed by meteoroids hitting the surface of the Moon. Besides, the cost of acquiring gems from the Moon will be prohibitive for the foreseeable future; if the most common lunar rocks were sold as souvenirs, they would carry a higher price than rubies.

Nevertheless, just as it was not the fantastic Fountain of Youth but rather the real land and plentiful natural resources that proved to be the wealth of the New World, so the treasures of the Moon will be found in less romantic notions. "Water is worth more than gold to a parched desert wanderer," runs a trite statement. But the statement is true for the Moon, and for the Moon can be extended to include oxygen. In fact, production of lunar oxygen for life support and fuel in low Earth orbit and beyond is already seen as an economic incentive to build a Moon base (e.g., Mendell 1985).

In general, because of the high energy cost of launching material into space from Earth's substantial gravity well, materials already in space (on the Moon, for example) gain value for construction projects there. Such materials could be used "as found" or after only simple processing. Lava tubes on the Moon could serve as early lunar shelters (Hörz 1985). In near-Earth space, lunar basalt could be used as heat shielding for vehicles reentering the Earth's atmosphere and could provide built-in protection for orbiting platforms (e.g., Nozette 1983). More extensively processed bulk materials for space construction might include concrete (see Lin 1985 and also Lin's subsequent paper in this volume) and glass (Blacic 1985) from the Moon.

*Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, St. Louis, MO 63130. We thank the National Aeronautics and Space Administration for partial support of this work through the NASA/University of Arizona Space Engineering Research Center.

Also because of the high cost of exporting materials from the Earth to the Moon, it is reasonable to imagine that a Moon base would, in the longer term, approach self-sufficiency, as eloquently proposed in the book *Welcome to Moonbase* (Bova 1987). What lunar resources make such a scenario feasible? The answer is found in the most common materials and conditions known on the Moon—the soil, the rocks, and the reliable supply of sunlight.

All the common soils on the Moon are rich in oxygen (about 45% by weight), silicon (about 21%), iron (6 to 15%), aluminum (5 to 13%), calcium (8 to 10%), magnesium (about 5%), and titanium (up to 6%). No ore bodies like those found on Earth have been proven to exist on the Moon, but some rock types have concentrated certain minerals; namely, ilmenite (rich in iron, titanium, and oxygen), anorthite (rich in calcium, aluminum, silicon, and oxygen), and olivine and pyroxene (rich in magnesium, iron, silicon, and oxygen). The chemical elements these soils and minerals contain are valuable in applications that range from construction to propulsion. And it may be economically possible to extract volatile elements present at low concentrations (such as carbon, hydrogen, and nitrogen) by heating the lunar soil (e.g., Haskin 1990).

The most promising early use for lunar resources is likely to be for energy. Energy for space transportation can come from lunar oxygen and hydrogen. Proposed energy exports include solar energy collected on the Moon and converted to microwaves (e.g., Criswell and Waldron 1985) and fuel in the form of ^{3}He for nuclear energy (e.g., Wittenberg, Santarius, and Kulcinski 1986) as well as chemical propellants (e.g., Thompson 1951, Arnold 1980, Mendell 1985). Considerable interest in chemical propellants has revolved around the extraction of oxygen (Mendell 1985), the most abundant and possibly the most immediately valuable of these lunar energy resources. It will be used as oxidant for fuel in the Earth-Moon system, and perhaps ultimately for flights to Mars if it can be provided at less cost than oxygen brought from the Earth (see, for example, Davis 1983 and Mike Simon's paper in volume 2, "Utilization of Space Resources in the Space Transportation System").

Oxygen From the Moon

Accepting, then, that oxygen, rather than gigantic gems or gold, is likely to make the Moon's Klondike, we have chosen to investigate the extraction of oxygen from the lunar soil. Unlike the Klondike, this strike will not be made by the prospector who discovers the location of the oxygen ore, for it is everywhere on the Moon. This strike will be made by the inventor who discovers the robust, economical process for extracting the oxygen. We think the process that will pan out will be electrolysis of molten soil. (See figure 21.) We are investigating it because it is conceptually simple and because its nontraditional character fits the nontraditional lunar materials and conditions.

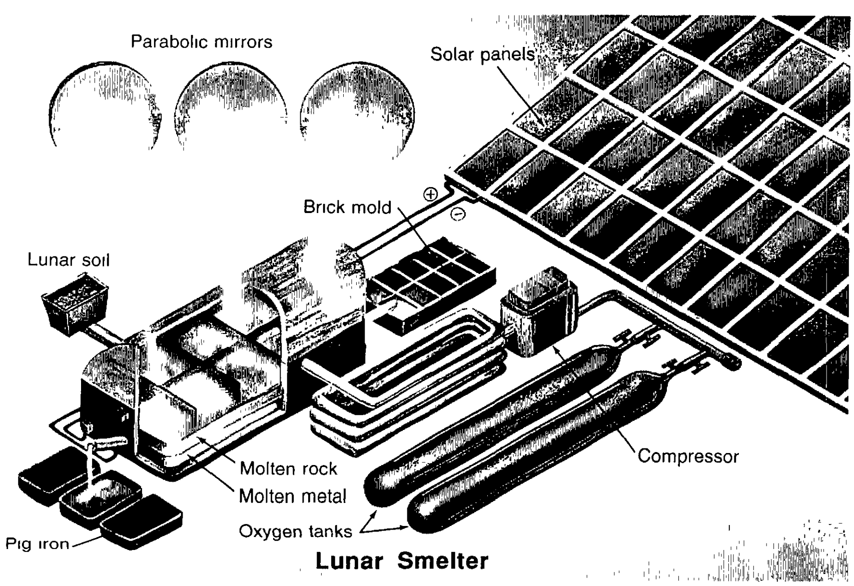

Figure 21

Electrolysis of Lunar Soil To Produce Oxygen and Iron (and Bricks)

In this early concept of the direct (without a flux) electrochemical reduction of lunar silicates, solar heat is used to melt the initial batch of lunar soil. Solar energy is also captured by panels of solar cells and turned into electricity, which charges both the anode and the cathode of the electrolysis unit. (We now think nuclear power may be more practical. In the absence of an efficient solar energy storage device, nuclear power would be needed to continue the electrolysis during the lunar night.) The oxygen that evolves at the nonconsumable anode is compressed and stored as a liquid. The molten metal that gathers at the cathode (itself molten metal) is bled off to form pig iron and other alloys. The residual slag might be formed into bricks or beams for structural purposes.

Illustration. Washington University in St. Louis

In our study of molten silicate electrolysis, we have taken the approach that the first step in developing the process is to understand its fundamental chemistry. This includes understanding the primary reactions that take place at the electrodes, the kinetics and energies of those reactions, competing reactions that might reduce the efficiency of oxygen production, and how melt resistivity changes with temperature and melt composition. The answers to these questions tell us whether the process is theoretically viable and competitive, presuming appropriate technologies can be developed to implement the process in real life and minimize dynamic problems arising during electrolysis (such as remixing of the product with the feedstock or insufficient mixing of the silicate melt). We have also begun investigating other specific questions about silicate melt electrolysis, such as durability of container and electrode materials and the nature and composition of the product. Our results are summarized here and are reported in more detail in Haskin et al. 1990, Colson and Haskin 1990, and Haskin and Colson 1990.

Process Theory

In molten silicate electrolysis, metal cations are reduced at the cathode to form metals, and silicate polymer chains are oxidized at the anode to form oxygen. The primary cathode reactions that produce metal are the following:

$$Fe^{2+} + 2\,e^- \rightleftharpoons Fe^0 \qquad (1)$$

$$Si(IV) + 4\,e^- \longleftrightarrow Si^0 \qquad (2)$$

The primary anodic reaction producing oxygen is reaction (3).

$$4\,(SiO^-) \longleftrightarrow 2(Si\text{-}O\text{-}Si) + O_2 + 4\,e^- \qquad (3)$$

The kinetics of these reactions are fast compared to the current densities expected in actual electrolysis, and reaction kinetics is not a serious constraint on the electrolysis process.

The efficiency of production is decreased and the energy required to produce a given amount of product correspondingly increased because of competing reactions at the anode and cathode. The most serious competing reaction at the anode in melts with high iron concentrations is oxidation of Fe^{2+}.

$$Fe^{2+} \rightleftharpoons Fe^{3+} + e^- \qquad (4)$$

The efficiency of oxygen production (defined as moles O_2 produced/ 4 times moles electrons* passed through the melt) depends primarily on the concentration of Fe^{2+} cations, with efficiency of oxygen production decreasing as Fe^{2+} increases.

The electrical conductivity of the melt also has a significant effect on the power requirement of the electrolysis process. We investigated the dependence of melt conductivity on melt composition and found that conductivity increases in a predictable fashion as the proportions of the oxides of silicon and aluminum in the melt decrease and as the proportions of the oxides of iron, magnesium, and calcium increase.

Power Requirements

The power requirement for molten silicate electrolysis can be numerically related to the oxygen production efficiency, the melt conductivity, and the dimensions of the electrolysis cell as follows. Power to drive the electrolysis equals $E \bullet I$, where I, the current required to get oxygen at the desired rate, is proportional to oxygen production rate/oxygen production efficiency. E, the potential required to drive the electrolysis, is roughly equal to $E_c - E_a - I(R_{cell})$, where $E_c - E_a$, the potential required to drive the reaction(s), is a function of the cation reduced (the absolute value of $E_c - E_a$ increases in the order Fe < Si,Ti < Mg,Al < Ca) and the concentrations of the cations in the melt. R_{cell}, the resistance of the electrolysis cell, is equal to $L/\kappa A$, where L is the distance between electrodes, A is the electrode surface area, and κ is the melt conductivity.

Calculated from this relationship and those above, the energy requirements expected for a realistic range of the variables L, A, O_2 eff, and κ are shown in figure 22. A comparison is made to energy requirements estimated for other processes. The estimated energy requirements for the molten silicate electrolysis process compare favorably with those for other processes even at the less favorable end of the range for the selected critical variables.

*A mole of electrons is Avogadro's number (6.023×10^{23}) of electrons.

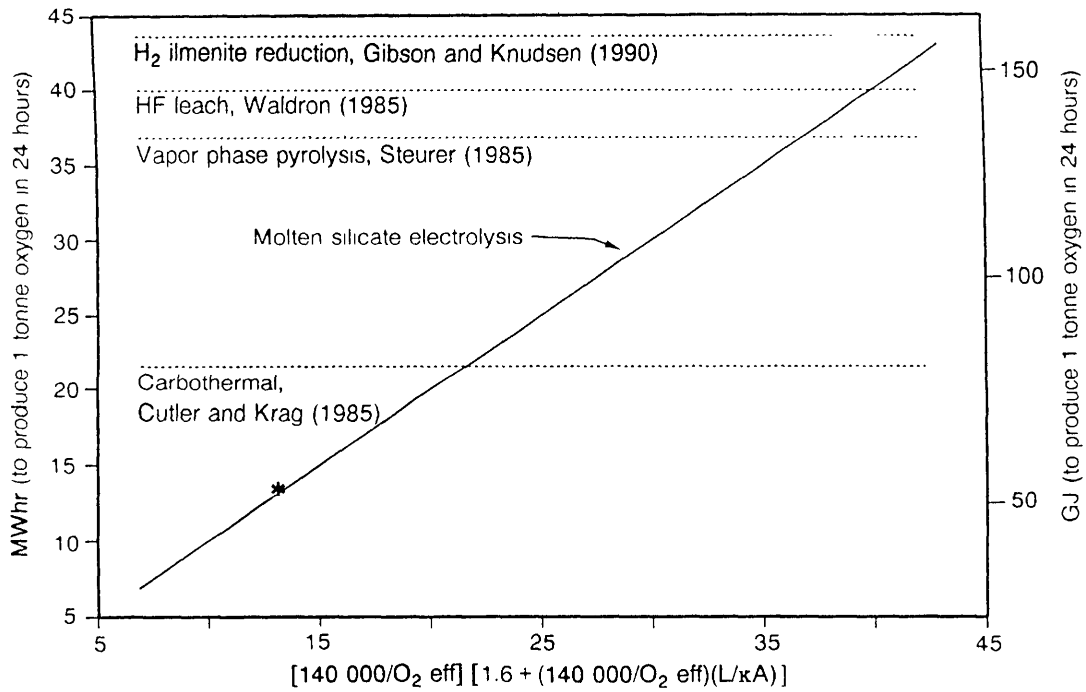

Figure 22

Energy Requirements for the Molten Silicate Electrolysis Process

The energy requirements for the molten silicate electrolysis process for extracting oxygen from lunar soil depend on the variables L (distance between electrodes), A (surface area of electrodes), O_2 eff (efficiency of oxygen production, defined in the text), and κ (melt conductivity).

The abscissa plots a term which numerically models the dependence of energy required for the electrolysis on these designated variables, as described in the text and in more detail in Haskin et al 1990 and Colson and Haskin 1990. It can be seen from the expression that the energy requirement increases as O_2 eff, κ, and A decrease and L increases. The range of values along the abscissa is a range we believe can realistically be achieved. The range is from O_2 eff = 90%, κ = 1 cm^{-1} ohm^{-1}, A = 30 m^2, and L = 0.5 cm to O_2 eff = 50%, κ = 0.08 cm^{-1} ohm^{-1}, A = 30 m^2, and L = 1 cm.

Presumably, an operating electrolysis cell could be maintained such that values for O_2 eff, κ, A, and L are the most advantageous (require the least energy).

The energy requirement calculated by Haskin et al. (1990) for a hypothetical electrolysis of a lunar soil is shown by an asterisk.

The term plotted along the abscissa has no bearing on the energy values reported for the alternative processes, which are shown for comparison purposes. These values are arbitrarily drawn as horizontal lines because they do not depend on the abscissa variables. It is seen that the energy required by the molten silicate electrolysis process compares favorably with that estimated for alternative processes.

Products of Molten Silicate Electrolysis

We have identified several products of silicate electrolysis, partly on the basis of our experiments and partly on the basis of phase diagrams for equilibrium processes. The main products are oxygen produced at the anode and a suite of metals and metal alloys produced at the cathode and consisting of iron, silicon, or iron-silicon alloys containing 0.2-1 percent titanium and chromium. The metal compositions vary as a function of imposed potential and magma composition. (Theoretically, but not yet observed in our experiments, aluminum, magnesium, and calcium could be reduced at increasingly negative potentials and at higher melt temperatures.)

The mineral spinel precipitates from the residual melt at sufficiently low temperature or with sufficient removal of silicon and oxygen. This material varies in composition from an iron- and chromium-rich spinel to a magnesium- and aluminum-rich spinel, depending on the composition of the magma and the extent of electrolysis.

The remaining molten silicate will be an important byproduct; it can be cast into bars, beams, and sheets, or its CaO- and MgO-enriched composition may make it suitable for use in cements. The so-called "waste heat" carried off with the products or radiated by the cell is another potentially useful byproduct.

Electrode and Container Materials

The primary disadvantage of the molten silicate electrolysis process is that these high-temperature silicate melts are very corrosive, and suitable materials for containers and electrodes are yet to be tested. We discuss here four general types of possible electrode or container materials.

One type of material is simply inert to the silicate and its products. As an example, platinum has been used extensively in experimental petrology as an inert container for silicate melts at temperatures as high as 1650°C. However, although platinum does not react with silicate melt, it does combine with silicon to form an alloy that melts below 1000°C. Because silicon is expected to form at the cathode and accumulate in the container, platinum is unsatisfactory as a cathode or container. Platinum does appear to be a suitable anode material (Haskin et al. 1990).

The second type of material involves a steady-state equilibrium. An "iron skull" container or cathode could be formed by balancing the heat generated by the electrolysis with heat lost to the surroundings to form a solid skin of product or feedstock enclosing the silicate melt and metal product.

The third type of material would be in thermodynamic equilibrium with the silicate melt and electrolysis products and would therefore not react with them. Because the product is Si-Fe metal, Si-Fe alloys might serve as the cathode material (Haskin et al. 1990). Similarly, the presence of spinel ($MgAl_2O_4$) on the liquidus of the residual silicate of the electrolysis process suggests the use of spinel as the containing material.

The fourth type of material would be destroyed by the process, but slowly. This option detracts from one of the intended advantages of unfluxed silicate electrolysis—the absence of any need to resupply reagents or other materials from Earth or to recover them from the products. Nevertheless, such an option may prove to be the most cost-effective.

Problems and Work Yet To Be Done

As discussed above, our first steps in the study of molten silicate electrolysis have been to investigate the fundamental chemistry of the electrolysis and to address some specific questions such as the product composition. We have not addressed certain complexities of the process such as (1) problems that might arise in scaling up from our small experiments to a factory-size process, (2) the problem of designing a system that will effectively transfer the corrosive electrolysis products from the cell, (3) the problem of maintaining the cell at high temperature so that the silicate melt does not freeze and destroy it, (4) the problem of getting ore from the lunar surface to the cell, and (5) the still untested state of our proposed container and electrode materials. Our purpose thus far has been not to demonstrate that molten silicate electrolysis in its current state of development is the best process, but to determine whether, theoretically and experimentally, it might be the best process if certain technological hurdles can be overcome. As do all the proposed methods for extracting oxygen from lunar materials, the silicate melt electrolysis method requires considerable work before an operational factory can be built.

Criteria for Comparing Processes

Several other promising processes for extracting oxygen from lunar materials have been proposed and are being studied, including reduction of ilmenite by hydrogen gas (see the preceding paper by Knudsen and Gibson), reduction by carbon monoxide gas (see the paper by Rosenberg et al.

preceding Knudsen and Gibson's), extraction by processing with hydrofluoric acid or fluorine (e.g., Waldron 1985; Burt 1989, 1990), and electrolysis using a fluxing agent to reduce the melting temperature and increase the electrical conductivity of the melt (e.g., Keller 1989). Understanding which of these processes is the most convenient, reliable, and economical is one of the goals of current research efforts. At present, we are the primary investigators of the molten silicate electrolysis method (also called the "magma electrolysis" method) for extracting oxygen from lunar materials, and our work to date has increased our confidence in its promise. Here, we compare our method, as we now assess it, with other proposed technologies. We recognize the fine line between advocacy and objectivity (Johnson 1980), and we realize that only the test of time and adequate experimentation can determine which technology is the most appropriate.

Informed speculation and preliminary studies of these and other extraction processes have proceeded for over three decades, but slowly for the following reasons: (1) The exact characteristics of nonterrestrial resources are, in most cases, only poorly known, although our knowledge of lunar resources is at least based on experience on the Moon's surface and materials collected there. (2) Conditions on the Moon (vacuum, intermediate gravity, extreme temperatures, and nontraditional ores) are foreign to Earth experience in mining and materials extraction. (3) Lunar conditions (with which we have little experience) and the uncertain future demand for lunar materials make significant investment of time and money in the development of specific processes seem risky. Thus, many studies have been of the paper, rather than the laboratory, variety.

Given the nontraditional ores and conditions on the Moon, it can be argued that nontraditional extraction processes may prove more practical there than transplanted terrestrial technologies (e.g., Haskin 1985). We form certain general criteria for judging the various processes as discussed below (and elsewhere in this volume).

The successful lunar process must rely on proven resources, preferably abundant ones. Especially in the short term, the cost of searching for specialized or superior ore bodies (which may or may not exist) could overwhelm the cost of extracting the desired material from less specialized ore. The use of a common material also requires that a process should accommodate a substantial range of feedstock compositions and thus be relatively insensitive to the selection of a Moon base site. The process should use a feedstock that is easily mined and requires minimal processing. It should operate automatically or by teleoperation from Earth. Particularly in the early days of Moon base development, the process and accompanying mining, beneficiation, and other operations should not require a large fraction of the astronauts' time or of the available power.

The process should not be compromised by, and if possible should take advantage of, lunar conditions such as 2-week days (with dependable sunlight—there are no cloudy days), large temperature swings between day and night, vacuum, intermediate gravity, abundant unconsolidated lunar "soils," clinging dust, and the absence of traditional processing agents such as air, water, coal, and limestone.

The process should be simple, with few steps and few moving parts. It must be easy to install and robust against physical jarring during transport and installation. Initially, all operations on the lunar surface will be awkward and expensive. Thus, the simplest technologies that can produce crucial products will presumably be the first technologies developed (Haskin 1985). Keeping the process simple will make it easier to automate, will require fewer replaceable parts, and should reduce operational problems, resulting in less downtime and fewer people needed to operate the plant. Simplicity can also decrease development time and cost. However, simplicity must be balanced against flexibility to yield more specialized products later on in the development of the Moon base. For example, some compromise should be reached between the ability to extract a single product from lunar soil and the ability to extract several valuable products by a more complex process or processes.

The process must require little or no continuing supply of reagents from Earth (such as fluorine, hydrogen, nitrogen, or carbon). One of the principal costs of setting up and maintaining a lunar factory will be the need to bring supplies from Earth (see Simon's paper in volume 2). If the process uses reagents that need to be recovered, their use raises power and mass requirements (in contrast to on Earth, where cheap reagents often need not be recovered) and increases the complexity of the process (since additional steps are required to recover them).

In addition to applying these first-order criteria, we can make rough comparisons of various processes for extracting oxygen by asking the following questions. How much power is required to produce a given amount of oxygen? What fraction of the feedstock is converted into products? What are the products of the process? What technology must be developed before the process is viable? What plant mass is required to produce oxygen at a given rate? What must yet be learned about the theory of the process before any or all of the questions above can be answered? Exact answers to these questions cannot be obtained until much more research is done, but in the next section we describe a possible magma electrolysis operation, pointing out its advantages as judged by these criteria. Similar comparisons between various methods for extracting oxygen were made earlier by Eagle Engineering (1988).

A Proposed Lunar Factory

We envision a single-step, single-pot, steady-state electrolysis process using common lunar soil as feedstock with little or no preprocessing. As the soil is fed into the cell, it is melted by "excess" electrical heat released into the melt owing to resistance. The total electrode surface area would be about 30 square meters each (because each electrode is divided into fins, as in a car battery), and the total cell volume about 1 cubic meter. The operating temperature would be between 1300°C and 1600°C depending on the type of container and electrode materials that are ultimately developed. The cell would produce 1.4 tonnes iron-silicon metal, 1 tonne oxygen, and about 3.5 tonnes slag in 24 hours, with an energy requirement of about 13 MWhr (or 47 GJ). The process would satisfy many of the criteria set forth above for early lunar technologies, including use of common and easily mined lunar soil as feedstock, absence of a need to supply reagents from Earth, and simplicity of the process combined with multiple products. Mass, size, and power requirements of the process are also competitive with alternative processes (table 9). The low energy and mass requirements of the process are particularly important because the major expense in establishing a lunar oxygen factory is the cost of transporting the plant materials (including the required power plant) to the Moon (see Simon's discussion in volume 2).

TABLE 9. *Comparison of Proposed Processes for Producing Oxygen From Lunar Soil*

	Electrolysis	Typical range for alternative processes*
Feedstock	Common soil	Common soil to beneficiated soil to ilmenite
Mass of mined material (per 1000 tonnes O2)	4 670 tonnes	4 600-120 000 tonnes
Reagents required	None	None to C, H, F
Temperature	1250-1400°C	700-3000°C
Plant energy (per tonne O2)	13 MWhr (47 GJ)	20-40 MWhr (72-144 GJ)
Plant mass (per 1000 tonnes O2 per year)	3-10 tonnes	5-80 tonnes
Product	Oxygen, Fe-Si alloy, slag	Oxygen with pure oxides or metals to oxygen plus slag
Primary advantage	Simplicity	E.g., good Earth analogs for process, many usable products, no consumables used, low-T operation
Primary disadvantage	Corrosive silicate, high-T operation, difficulty restarting after cooldown	E g., complexity, high-T operation, low oxygen/reagent ratio, low product/ore ratio, high energy or mass required

*Values calculated from Eagle Engineering 1988 and references therein

Conclusions

All the processes that have been suggested for extracting oxygen from lunar materials and probably many that haven't yet been suggested deserve our careful consideration in determining which is the "best" process to be implemented on the Moon. However, all the processes require substantial additional study before we are able to judge their relative worth for extracting lunar oxygen; and, before an operational plant can be built, even more study will be required.

We note that there is not much time (we hope) before the chosen process will be needed on the Moon. If we are to ensure that an oxygen production plant is included in the early planning and development of a lunar base, we need to progress quickly in assessing the various proposed processes so that the concept of a lunar oxygen plant can become a part of everyone's idea of what a lunar base should be.

Although it is certainly too early to decide which oxygen extraction process is the best one, our preliminary work with magma electrolysis has increased our confidence in its promise. We feel that its theoretical advantages listed above, including relatively low energy requirements, low mass, simplicity, and versatility with respect to feedstock, are sufficient to warrant its consideration as one of the processes most likely to be used in the early mining of oxygen from the Moon.

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Vapor Phase Pyrolysis

Wolfgang Steurer

The vapor phase pyrolysis process is designed exclusively for the lunar production of oxygen. In this concept, granulated raw material (soil) that consists almost entirely of metal oxides is vaporized and the vapor is raised to a temperature where it dissociates into suboxides and free oxygen. Rapid cooling of the dissociate vapor to a discrete temperature causes condensation of the suboxides, while the oxygen remains essentially intact and can be collected downstream. The gas flow path and flow rate are maintained at an optimum level by control of the pressure differential between the vaporization region and the oxygen collection system with the aid of the environmental vacuum.

The process is illustrated in figure 23 in the form of a conceptual facility. The particle feedstock is dispensed from a gravity feed unit to a crucible. There it is vaporized and dissociated by means of thermal energy supplied by a solar concentrator whose focal point is at the crucible. The beam enters the vacuum-sealed unit through a self-cleaning window at a distance where the concentration is still low enough to preclude overheating of the window.

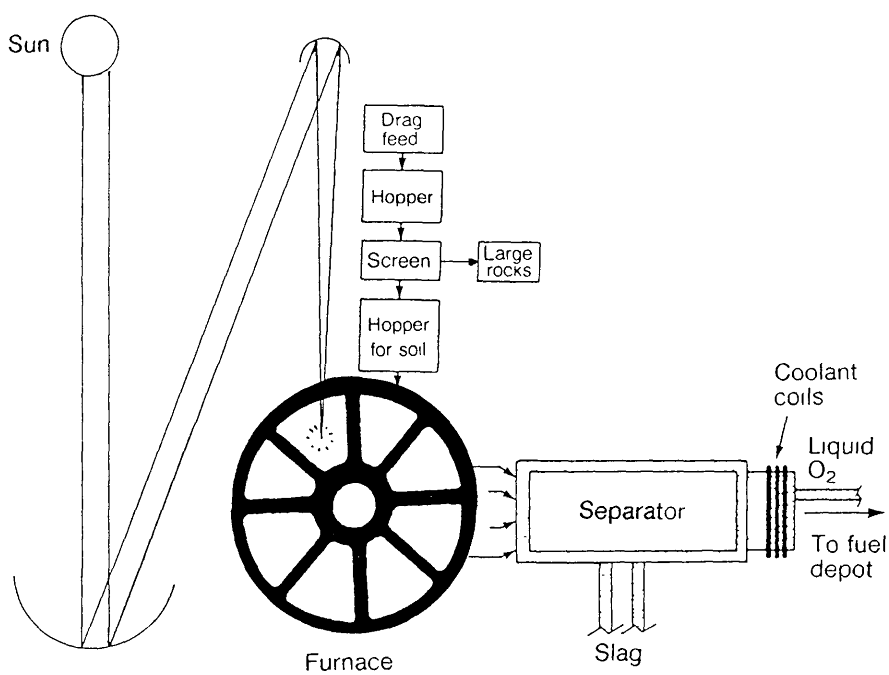


Figure 23

Vapor Phase Separation Processor

The vapor phase pyrolysis method of oxygen production starts with soil being screened so that the larger rock fragments are removed. The soil is then transferred from the hopper to chambers of the furnace, which in this concept rotate from the hopper position to the focus of the solar concentrator. Along with that rotation, the crucible is sealed so that the gases extracted when the soil is heated do not return to the lunar vacuum. The beam enters the sealed unit through a self-cleaning window at a distance where the concentration is still low enough to preclude overheating of the window. Thermal energy is concentrated at the crucible in the furnace, where it vaporizes the soil and dissociates (ionizes) the vapor to produce a plasma. The dissociated gases pass through a rapid cooling system (separator) which condenses the suboxides, and the remaining oxygen is liquefied.

The dissociated gases pass then through a rapid cooling separator at a yet-to-be-determined optimum flow rate and flow pattern. The cooling column may, in reality, be considerably longer than shown in the sketch. The produced oxygen may be collected as gas in a balloon (with a shade/shield to protect it from the Sun's heat and from micrometeorite strikes) or liquefied. The problems of oxygen storage and liquefaction are common to all oxygen-producing processes and are, therefore, not addressed here.

The preferred raw material, in view of the ease of acquisition, is lunar basalt in the form of regolith (soil). Since it consists of a variety of metal oxides, numerous individual species are obtained during dissociation. For SiO_2, TiO_2, and Al_2O_3, for example, the major (minor) species produced are

$SiO_2 \quad O_2 + SiO\ (+\ SiO_2)$

$TiO_2 \quad O_2 + TiO\ (+\ TiO_2)$

$Al_2O_3 \quad O_2 + AlO_2\ (+\ AlO + Al_2O + Al_2O_2)$

The relative importance of the individual dissociation species can be measured by their partial pressures which, in turn, increase rapidly with the processing temperature. For a mixture of oxides representative of lunar soil, the partial pressures of the species evolving from three major oxides in the temperature regime from 2000 to 3000 K are listed in table 10. (To convey a clear overview, negligible pressures below 10^{-6} atm are given in orders of magnitude only.)

An examination of table 10 substantiates the following conclusions: (1) The processing temperature should be close to 3000 K (the limit for solar heating). (2) The gas composition is dominated by O_2 and SiO. The oxygen pressure at 3000 K of roughly 1/10 of an atmosphere is more than adequate for production rates.

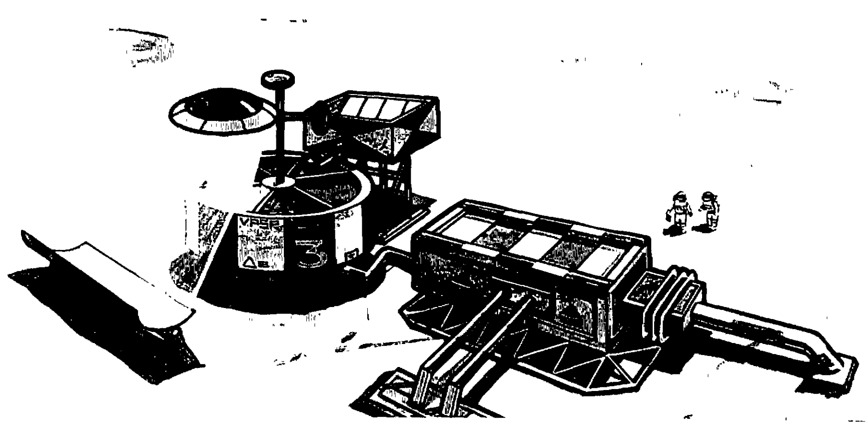


TABLE 10. *Partial Pressures of Dissociation Species of Lunar Regolith at Three Temperature Levels*
[In atmospheres (1 atm = 10^5 N/m^2)]

Gas species	2000 K	2500 K	3000 K
O_2	3.2×10^{-6}	1.5×10^{-3}	8.1×10^{-2}
AlO	(10^{-12})	(10^{-8})	1.8×10^{-5}
AlO_2	(10^{-11})	(10^{-7})	5.8×10^{-5}
Al_2O	(10^{-16})	(10^{-11})	(10^{-8})
Al_2O_2	(10^{-17})	(10^{-12})	(10^{-9})
SiO	6.5×10^{-6}	3.0×10^{-3}	1.6×10^{-1}
SiO_2	(10^{-7})	1.4×10^{-4}	1.1×10^{-2}
TiO	(10^{-10})	1.0×10^{-6}	1.0×10^{-4}
TiO_2	(10^{-11})	(10^{-7})	1.3×10^{-5}
FeO	1×10^{-6}	2.0×10^{-4}	5.9×10^{-3}

The oxygen yield as a fraction of the raw material throughput is determined from the partial pressure and molecular weight of each species by the relationship

$$O_2\text{/throughput} = \frac{p_{O_2} \times M_{O_2}}{\sum (p \times M \text{ of each species})}$$

The resulting oxygen yield is on the order of 20 percent.

The processing energy required for vaporization and dissociation of the entire throughput is 5100 kWhr/t and for cooling 2000 kWhr/t, adding to a total of 7100 kWhr/t. Using the oxygen yield of 0.20, this translates into 35 500 kWhr/tonne of oxygen produced.

Most of this amount could be provided by solar thermal energy using suitable concentrators; however, some electrical power will probably be needed. Additional energy would be required for support operations, such as material acquisition, transport, and beneficiation, or conditioning of the oxygen for storage. To answer the energy supply question, a more specific design and further analysis of possible tradeoffs are necessary.

While vapor phase pyrolysis is basically a continuous process, periodic shutdown is necessary for removal of the condensed suboxides from the cooling system.

In summary, vapor phase pyrolysis may be a viable process for producing oxygen from lunar materials. It is straightforward and does not require complex equipment. Its biggest disadvantage is the large amount of energy it requires. However, this energy requirement might be reduced by efficient use of solar energy, by recovering heat from the slag, and by using the recovered heat to preheat the feedstock. While such techniques would add complexity, the savings in energy might be worth the cost in added equipment. In any case, vapor phase pyrolysis clearly deserves additional development work.

Plasma Separation

Wolfgang Steurer

This process employs a thermal plasma for the separation and production of oxygen and metals. It is a continuous process that requires no consumables and relies entirely on space resources. The almost complete absence of waste renders it relatively clean. It can be turned on or off without any undesirable side effects or residues. The prime disadvantage is its high power consumption.

In the basic concept, the process consists of the following steps: Granulated raw material, such as lunar regolith, is vaporized, dissociated, and finally brought to a temperature where a thermal plasma is obtained. The plasma permits electromagnetic manipulation and separation of the ionized species according to their positive or negative charges.

In the process discussed here, a unique concept is introduced and designated "selective ionization." Metals exhibit a low ionization potential, below 9 eV, while the lowest ionization potential of gases is 13.6 eV (oxygen). In a thermal plasma, where the degree of ionization is related to temperature, this gap in the ionization potential defines a temperature range, between 8 000 and 10 000 K, in which metals approach 100-percent ionization while the atomic oxygen remains essentially neutral (ionized O_2 less than 1 percent). Under these conditions, only metals respond to electromagnetic forces and, consequently, can be separated from the neutral oxygen.

To substantiate this effect, theoretical data were generated for the metals of interest and for oxygen by programming the well-accepted Saha equation. The data on the number densities of the positive ions, neutral species, and electrons at temperatures from 4 000 to 14 000 K were translated into percent ionization. The results, plotted in figure 24, clearly show the wide gap in the degree of ionization for the metals concerned and oxygen between 8 000 and 10 000 K.

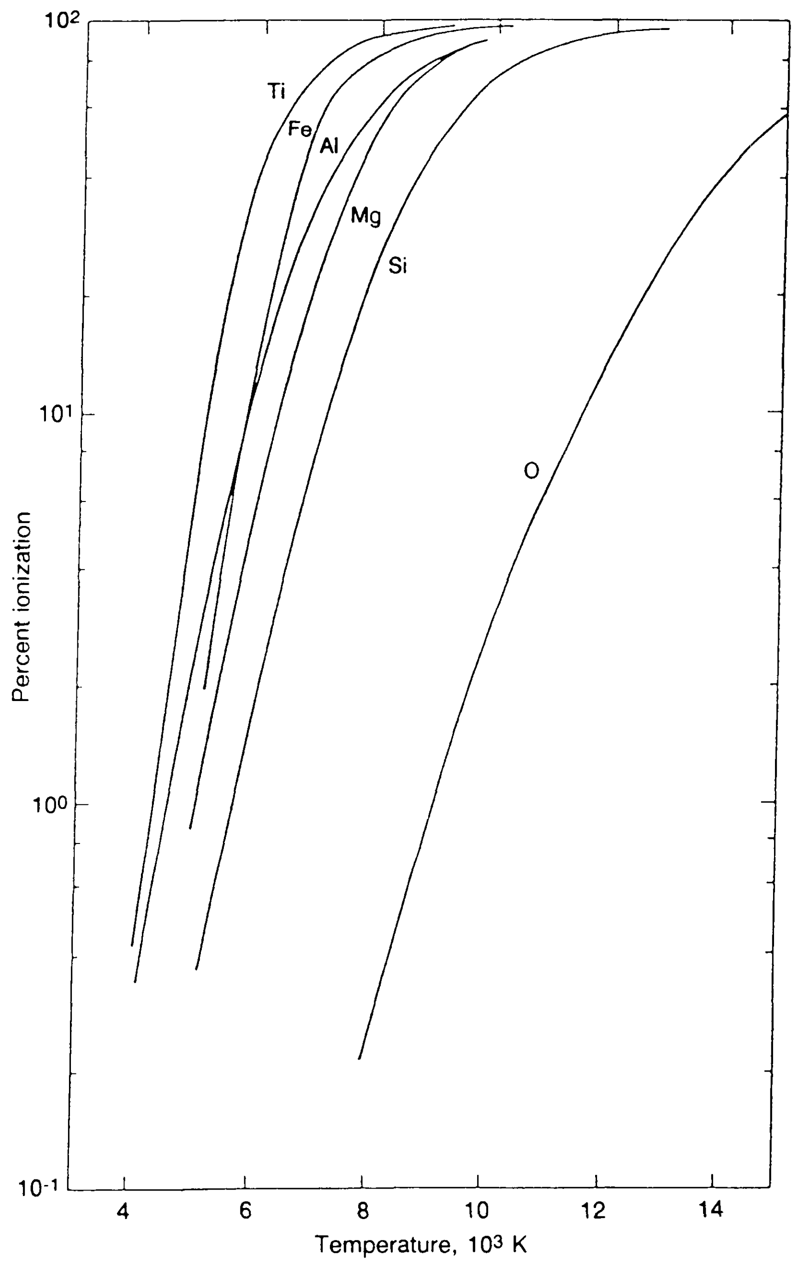


Figure 24

Percent Ionization of Metal and Oxygen vs. Temperature

In the proposed process, the dissociated gas is heated to 9 000 K by inductive coupling and the selectively ionized plasma is passed through an electrostatic field for separation. As shown in figure 25, the positive metal ions are diverted toward the cathode half-shell. The neutral oxygen continues to flow downstream and is recovered at the end of the column in an appropriate collection system.

A conceptual processing facility is shown in figure 26. The ions of each individual metal follow a specific trajectory and deposit, therefore, at distinct distances in the electrostatic system. This fact implies the possibility of recovering individual metals rather than a metal mixture.

While the process is basically continuous, it requires periodic removal of the metal deposits

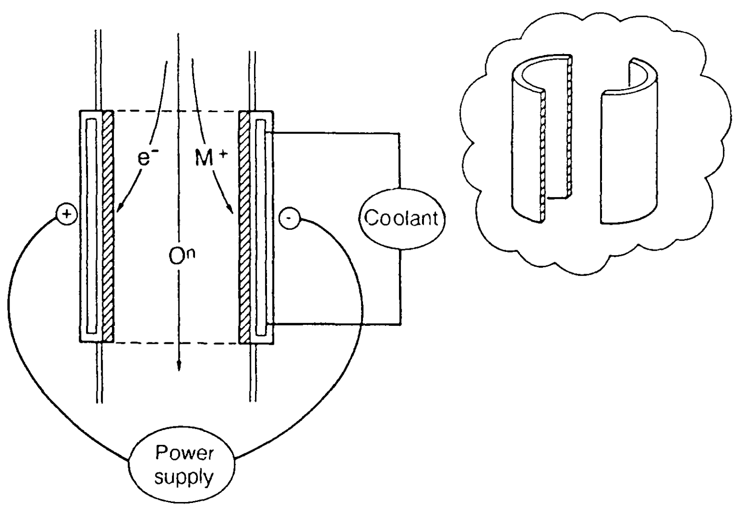


Figure 25

Selective Ionization and Electrostatic Separation

from the cathode. Since there is essentially no waste, the combined process yield of metals and oxygen approaches 100 percent. Conservative yield factors (fraction of throughput) are as follows:

Metals	0.51
Oxygen	0.39
Total	0.90

Total energy requirements are approximately 13 300 kWhr per tonne of all products. Of this, 4500 kWhr/t can be satisfied by direct solar heating/vaporization /dissociation. The remaining 8800 kWhr/t has to be supplied in the form of electric power.

This figure has to be increased by a factor of 2.2 for power conditioning and losses, resulting in an actual power consumption of 19 360 kWhr/t. A yearly combined production of 500 tonnes of metals and oxygen, equivalent to 125 kg per hour, calls for an electric power generation capacity of 2400 kW (installed).

This assessment is based on the use of inductive heating for plasma generation. There may be other alternatives, such as laser heating, which may simplify the problem of plasma containment. However, the effect of such alternate concepts on power requirements is not expected to be substantial.

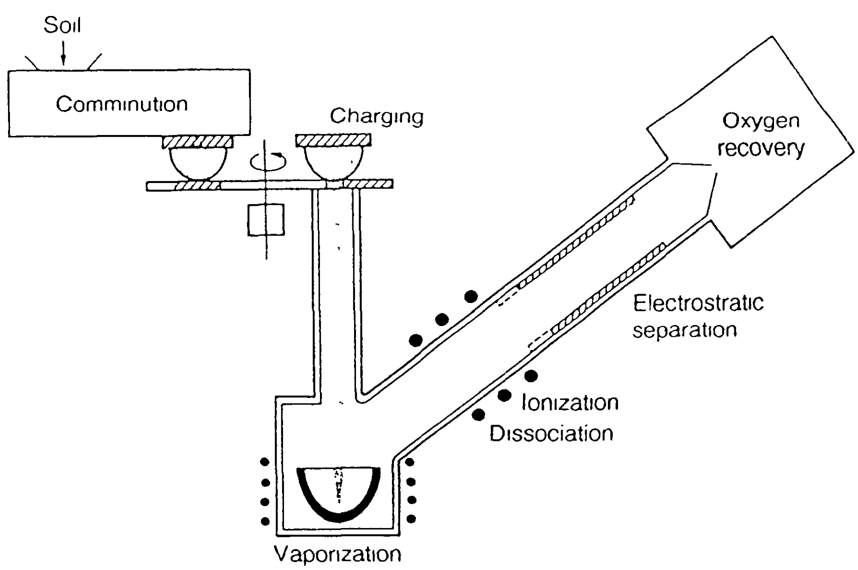


Figure 26

Plasma Separation: Conceptual Apparatus

Processes for Metal Extraction

David F. Bowersox

The cost of transportation from Earth to the Moon is so high that proposals for industrial efforts on the Moon are often limited to native (lunar) materials. This restriction, fortunately, can be greatly eased if recyclable elements are shipped from Earth and reused. The initial, nearly prohibitive costs are alleviated by the repeated operation. The expenses of the reagents, like those of the shelter and special equipment, are spread over a relatively long program. This report describes the processing of plutonium at Los Alamos National Laboratory (LANL), an operation illustrating concepts that may be applicable to the processing of lunar materials. The toxic nature of plutonium requires a highly closed system, just as the expense of transporting reagents to the Moon requires a highly closed system for processing lunar surface materials.

To illustrate the benefit of using a closed pyrometallurgical process on the Moon, let us take the reduction of ilmenite as an example. Ilmenite ore can be isolated and beneficiated, and usable quantities of oxygen, iron, and titanium can be extracted from the ore. The first step might be a hydrogen reduction step, in which hydrogen is reacted with the ilmenite ore to produce water and a slag of iron mixed with titanium dioxide. By following this step with electrolysis of the water, we can recover the hydrogen and produce oxygen for life support and propulsion.

Let us now consider expanding the ilmenite process by adding a step in which the iron-titania slag is treated so as to obtain metallic iron and titanium dioxide or, even better, metallic iron and metallic titanium. Two additional processes are suggested—a carbonyl process for separating the metallic iron from the slag or from titanium and a pyrochemical process to produce titanium metal.

The carbonyl process would separate iron (or nickel or other metals) from titania (TiO_2) or titanium metal by the reaction

$$Fe + 5CO \longrightarrow Fe(CO)_5$$

The compound can then be decomposed and the carbon monoxide recycled. This well-known method is compact and requires very little power.

The pyrochemical reduction of TiO_2 to metallic titanium may be carried out in a manner analogous to the process used to extract plutonium from scrap residues. Although the process is not directly applicable to nonterrestrial industrialization in its detailed steps, the success of this method indicates that it should be excellent for space programs if it can be applied to the extraction of other metals.

First, because of the solubilities and densities of the phases, the system is compact. Pyroprocessing requires approximately one-tenth the volume of aqueous processing. Operations could be remote and automated. Processes are either batch or semicontinuous, depending on the desired throughput. Reagents are generally recyclable, and residues, when produced, are in compact, dense form.

The major steps for plutonium processing are outlined in figure 27. The roasting step (1) would not be necessary in any nonterrestrial application; the starting material would already be in oxide form. The oxide, calcium metal, and excess $CaCl_2$ are reacted (step 2) in a magnesium oxide crucible where the plutonium is reduced to the metal by the reaction

$$PuO_2 + 2Ca \xrightarrow{CaCl_2} Pu + 2CaO \quad (2)$$

The calcium oxide dissolves in the calcium chloride and the metallic plutonium settles as a button, which is mechanically separated from the salt. In a nonterrestrial application, titanium and iron could form a metal button and then be separated by vacuum distillation or the carbonyl process. And the reactant metal could be calcium or perhaps aluminum. We at LANL are developing a method for recovering the calcium chloride for recycling.

If, in the plutonium process, the americium concentration is greater than 1000 ppm, it is lowered by equilibration at 800°C with sodium chloride/potassium chloride eutectic salt containing magnesium chloride as an oxidizing agent (step 3). The reactions are

$$2\ Am^0 + 3\ MgCl_2 \rightleftharpoons 2\ AmCl_3 + 3\ Mg \quad (3)$$

$$2\ Pu^0 + 3\ MgCl_2 \rightleftharpoons 2\ PuCl_3 + 3\ Mg \quad (4)$$

$$2\ Am^0 + 2\ PuCl_3 \rightleftharpoons 2\ AmCl_3 + 3\ Mg + 2\ Pu^0 \quad (5)$$

Under the conditions of the plutonium process, the salt contains most of the americium and 4 percent of the plutonium, while the plutonium, magnesium, and about 100 ppm americium are in molten form. The salt can be treated with calcium to extract the americium and plutonium and subsequently be reused. Although this is an important part of the plutonium process, it would not be necessary in a titanium recovery process. In both cases, however, because there is excess calcium and magnesium in the metal button, heating above the melting point is necessary to remove these volatiles. The product of this step is a solid metal, typically in the form of a solid metal cylinder formed by chill casting.

In the fourth step, purification of the metal, the cylinder of plutonium is placed in the anode cup of a magnesium oxide crucible, a sodium chloride/potassium chloride eutectic added, and electrolysis conducted at 750°C. The impure plutonium is ionized by giving up electrons at the anode. Then the ions migrate to the cathode to get electrons and deposit as pure plutonium. The reactions are

$$\text{Pu (impure)} \longrightarrow \text{Pu}^{3+} \text{ (anode)} \quad (6)$$

$$\text{Pu}^{3+} \longrightarrow \text{Pu}^{0} \text{ (pure)} \text{ (cathode)} \quad (7)$$

Input	Process	Output
	Step 1: Oxide Preparation	
Heat, O_2 ⟶		⟶ O_2
	$Pu \text{ (scrap)} + O_2 \longrightarrow PuO_2 \text{ (s)}$	
	Step 2: Metal Production	
Ca, $CaCl_2$ $\xrightarrow{850°C}$	$PuO_2 + 2Ca \xrightarrow{CaCl_2} Pu + 2CaO$	⟶ $CaCl_2 \cdot CaO$
	Step 3: Metal Preparation	
$NaCl \cdot KCl$, $MgCl_2$ $\xrightarrow{800°C}$	Americium removal (molten salt extraction)	⟶ $NaCl \cdot KCl$, $MgCl_2$, $PuCl_3$, $AmCl_3$
	Metal shaping, volatile recovery	⟶ Pu skull
	$2\,Am^0 + 3\,MgCl_2 \rightleftharpoons 2\,AmCl_3 + 3\,Mg$	
	$2\,Pu^0 + 3\,MgCl_2 \rightleftharpoons 2\,PuCl_3 + 3\,Mg$	
	$2\,Am^0 + 2\,PuCl_3 \rightleftharpoons 2\,AmCl_3 + 3\,Mg + 2\,Pu^0$	
	Step 4: Metal Purification	
$NaCl \cdot KCl$ $\xrightarrow{750°C}$		⟶ $NaCl \cdot KCl$, $PuCl_3$ (10%), $AmCl_3$
		⟶ Pu^0 (impure)
	Pu^0 (impure) Anode ⟶ Pu^0 (pure) Cathode	

Figure 27

Pyroprocessing of Plutonium at Los Alamos

Approximately 10 percent of the plutonium is in the salt phase and 10 percent remains in the anode as a solid when the electrorefining is completed. The cathode metal is 99.99-percent pure plutonium. The salt can be reused or treated to remove the plutonium trichloride, and the anode metal can be oxidized to remove impurities and then reduced in the metal production step.

This process has been developed over a period of years and is used successfully at Los Alamos National Laboratory. Changes are being made to optimize the process. However, the concept, with its compactness and its recycling of reagents, seems particularly transferable to nonterrestrial processing. The process requires no water, and the availability of high vacuum and heat sources (such as a solar furnace) should be advantageous in developing a successful process off Earth. In the space context, the availability of a reactant metal may be a problem. If aluminum could be scavenged from space vehicles, or lunar calcium be used and recycled, the economics would be enhanced.

Bioprocessing of Ores: Application to Space Resources

Karl R. Johansson

Introduction

The role of microorganisms in the oxidation and leaching of various ores (especially those of copper, iron, and uranium) is well known. (Among the review articles and reference books on this subject are Brierley 1978 and 1982; Brock, Smith, and Madigan 1984; Decker 1986; Ehrlich 1981; Kelly, Norris, and Brierley 1979; Krumbein 1983; Lundgren and Silver 1980; and Torma and Banhegyi 1984.) This role is increasingly being applied by the mining, metallurgy, and sewage industries in the biobeneficiation of ores and in the bioconcentration of metal ions from natural receiving waters and from waste waters high in toxic metals (Belliveau et al. 1987, Ehrlich and Holmes 1986, Hutchins et al. 1986, Nicolaidis 1987, Olson and Brinckman 1986, Olson and Kelly 1986, Thompson 1986, Torma 1987a and b, Tsezos 1985, Volesky 1987, Woods and Rawlings 1985). See figure 28.

Figure 28

Bacterial Processing of Metal Ores

Although most concepts of processing lunar and asteroidal resources involve chemical reactors and techniques based on industrial chemical processing, it is also possible that innovative techniques might be used to process such resources. Shown here are rod-shaped bacteria leaching metals from ore-bearing rocks through their metabolic activities. Bacteria are already used on Earth to help process copper ores. Advances in genetic engineering may make it possible to design bacteria specifically tailored to aid in the recovery of iron, titanium, magnesium, and aluminum from lunar soil or asteroidal regolith. Biological processing promotes the efficacy of the chemical processes in ore beneficiation (a synergistic effect).

Taken from Brierley 1982.

The question of harnessing bacteria for the beneficiation of ores on the Moon, on asteroids, or on Mars has been raised and must be seriously considered in the context of the utilization of space resources. Because of the almost total lack of organic matter on the Moon, it is fortunate that most bacteria known to participate in acid leaching of ores are autotrophic (derive all their carbon from carbon dioxide) as well as chemolithotrophic (derive energy through oxidation of reduced inorganic compounds or elements; e.g., hydrogen sulfide or ferrous ions). Furthermore, they satisfy all of their nutritional needs with inorganic substances, including certain trace elements known to be present in the Moon's regolith. But the development of biological processes to extract and purify ores on the Moon is severely constrained by the environmental conditions: the lack of elemental oxygen; the limited carbon, nitrogen, and hydrogen; the apparent lack of water; and the extremes of temperature and radiation. Thus, microbial ore processing must be established within a gas-tight enclosure. The enclosure must allow replenishment or augmentation of nutritional needs, retain moisture, maintain a suitable temperature, and protect the cells from radiation. See figure 29.

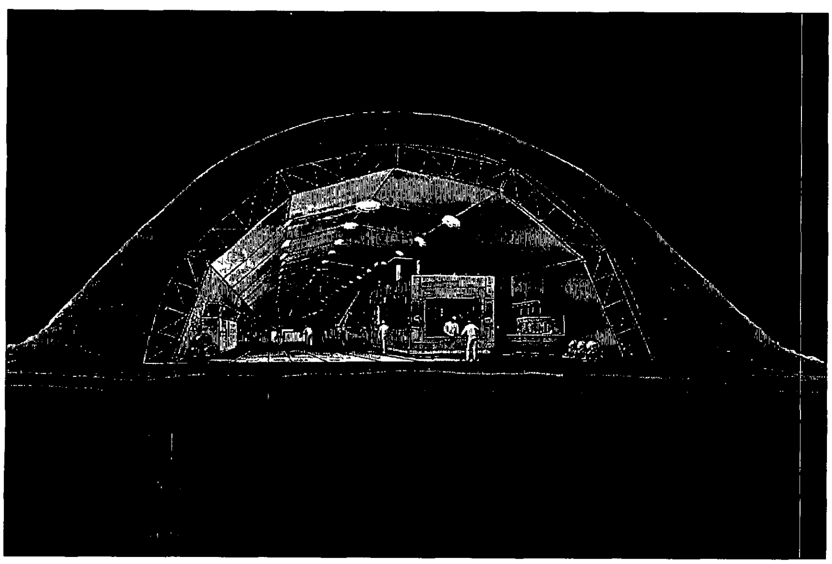


Figure 29

Enclosure for Microbial Ore Processing

A variety of pressurized enclosures have been proposed for a lunar base. In this concept by Fluor Daniel and Rockwell International, a large hangar-like enclosure functions as a workshop and servicing area. A microbial ore-processing complex could be totally enclosed by such a building. Ore could be introduced through airlocks and processed in a moist atmosphere at an appropriate temperature. Spent ore could be removed through airlocks, and waste products could be recycled. The key point is that the harsh environment at the lunar surface can be suitably modified to provide an optimum environment for ore processing.

Artist: Renato Moncini

Various kinds of interactions between microorganisms and metals are known: (1) beneficial as well as toxic effects of metals on metabolism, (2) oxidation-reduction reactions, (3) solubilization of metals through acids produced by microbial growth, (4) precipitation of metals by pH increases, (5) conjugation of metals and organic compounds, (6) metabolic transformation of metals, and (7) accumulation of metals either on the inside or on the outside of cells. In this paper I will consider the processes that are particularly important to the technology of metal recovery. Some of them may have application in the space environment. However, essentially no research has been done with this application in mind.

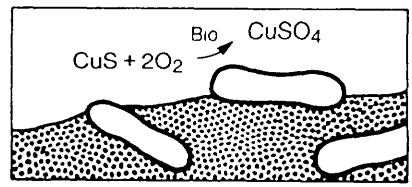
Acid Leaching of Ores

Acid leaching is a hydrometallurgical process resulting in the solubilization of ore minerals through chemical and biological oxidations and reductions of sulfur, iron, and certain other metals.

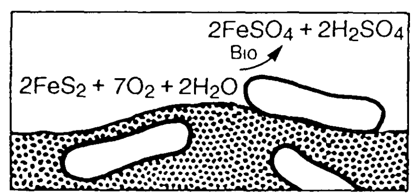
The Chemistry

The chemistry of the process is complex and greatly affected by pH, oxidation-reduction potential, dissolved oxygen, and temperature. (Some of the authorities describing this chemistry are Hutchins et al. 1986; Kelly, Norris, and Brierley 1979; Lundgren, Valkova-Valchanova, and Reed 1986; Torma and Banhegyi 1984; and Torma 1987a.) For example, bacteria can catalyze and drive the following oxidations:

$$^{*}MS + 2\ O_2 \longrightarrow MSO_4 \qquad (1)$$

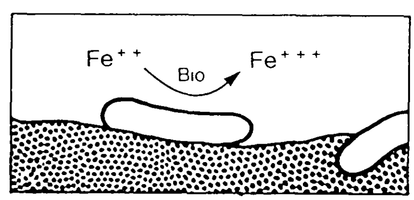


$$^{*}MS + 5\ O_2 + 2\ H_2O \longrightarrow MSO_4 + 2\ H_2SO_4 \qquad (2)$$



$$Fe^{++} \longrightarrow Fe^{+++}$$

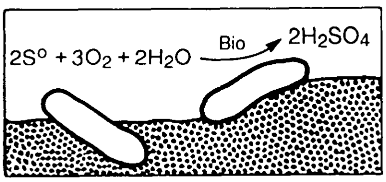
(ferric iron is regenerated) (3)



$$2\ S^0 + 3\ O_2 + 2\ H_2O \longrightarrow 2\ H_2SO_4 \qquad (4)$$

*M = Fe, Cu, Mo, Sb, Pb, Ag, Co, Ni, Cu-Fe, As-Fe, Ni-Fe, Zn-Fe, Cu-Se, etc.

(Thionate, tetrathionate, thiosulfate, and sulfite are also oxidized by some bacteria.)



$$H_2S + 2\ O_2 \longrightarrow H_2SO_4 \quad (5)$$

Chemically, ferric sulfate (largely generated through bacterial oxidation of ferric sulfide or ferrous ions) and sulfuric acid (largely generated through bacterial oxidation of ferric and other metal sulfides, elemental sulfur, or hydrogen sulfide) oxidize and solubilize numerous minerals; for example,

$$2\ FeS_2 + 2\ Fe_2(SO_4)_3 \longrightarrow 6\ FeSO_4 + 4\ S^0 \quad (6)$$

$$Cu_2S + 2\ Fe_2(SO_4)_3 \longrightarrow 2\ CuSO_4 + 4\ FeSO_4 + S^0 \quad (7)$$

$$Bi_2S_3 + 3\ Fe_2(SO_4)_3 \longrightarrow Bi_2(SO_4)_3 + 6\ FeSO_4 + 3\ S^0 \quad (8)$$

$$\boxed{CuFeS_2 + 2Fe_2(SO_4)_3 \xrightarrow{\text{Chemical}} CuSO_4 + 5FeSO_4 + 2S^o}$$

Another example of ferric sulfate leaching

$$UO_2 + Fe_2(SO_4)_3 \longrightarrow UO_2SO_4 + 2\ FeSO_4 \quad (9)$$

$$\boxed{UO_2 + Fe_2(SO_4)_3 \xrightarrow{\text{Chemical}} UO_2SO_4 + 2FeSO_4}$$

Solubilization of uranous oxide

$$2\ {}^*M + O_2 + 2\ H_2SO_4 \longrightarrow 2\ MSO_4 + 2\ H_2O \quad (10)$$

$${}^*MO + H_2SO_4 \longrightarrow MSO_4 + H_2O \quad (11)$$

The Bacteriology

The principal bacteria catalyzing reactions 1 through 5 are mixed populations of *Thiobacillus ferrooxidans, Leptospirillum ferrooxidans, Thiobacillus thiooxidans*, and several other species of acidophilic thiobacilli. There also exist some thermophilic thiobacilli which are facultative autotrophs inasmuch as they can utilize certain organic substrates in the environment. *Thiobacillus ferrooxidans* is unique in that it derives energy from oxidations of sulfur and reduced iron, copper, and tin; it also fixes nitrogen. *Thiobacillus thiooxidans* cannot oxidize iron; rather, it oxidizes sulfur and probably zinc sulfide. *Leptospirillum ferrooxidans* will oxidize only the soluble form of iron (Fe^{++}), but in conjunction with certain other sulfur-oxidizing thiobacilli it will synergistically oxidize pyrite (FeS_2) as well as chalcopyrite ($CuFeS_2$).

Another group of bacteria, the genus *Sulfolobus*, which is widely distributed in volcanic vents and thermal springs, is able to oxidize sulfur and iron at temperatures of 80°C, or even a few degrees higher. Sulfolobi are also able to grow in the absence of molecular oxygen provided Mo^{6+} or Fe^{+++} are present to serve as electron acceptors, thereby replacing O_2 as the ultimate electron acceptor. They are facultative heterotrophs and occupy a unique niche in the bacterial kingdom as *Archaebacteriaceae*, a family possessing a cell membrane composed of a long-chain, ether-linked hydrocarbon monolayer (instead of a phospholipid bilayer) and lacking a peptidoglycan cell wall, which is found in all other bacteria (Kelly and Deming 1988). Whether these and certain other archaebacteria play a significant role in thermophilic leaching of ores can only be surmised.

A filamentous, moderately thermophilic, sulfur-oxidizing, autotrophic bacterium, *Thermothrix thiopara*, also flourishes in volcanic vents and in thermal springs (Brierley 1982) and may play a role in the leaching of ores. Similarly, the filamentous, mesophilic bacteria *Thiothrix* and *Beggiotoa*, which oxidize sulfide to elemental sulfur, have potential for ore beneficiation.

The Commercial Leaching Operation

The release and recovery of metals from ores are facilitated by methods designed to amplify the requisite oxidation-reduction reactions (Brierley 1978, Brierley 1982, Campbell et al. 1985).

Dump leaching: This operation is usually applied to the extraction of copper from low-grade oxide or sulfide ores which are hauled as uncrushed stones from open-pit mines to enormous dumps (see fig. 30). The dumps are sprinkled with water and the percolate is collected in a natural or artificial catch basin. The copper is removed from the acidic leachate by cementation (with iron), electrolysis, or solvent extraction; the solution is then recycled through the dump. The operation continues for years during which time sulfur- and metal-oxidizing bacteria grow extensively to perpetuate the leaching process.

$$CuSO_4 + 5Fe \xrightarrow{\text{Chemical}} FeSO_4 + Cu^0$$

Cementation

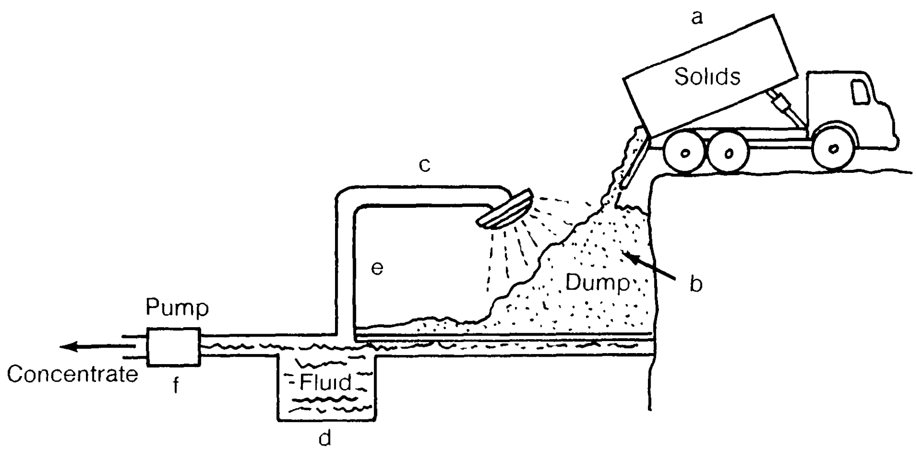


Figure 30

Dump Leaching

Uncrushed stones of low-grade oxide or sulfide ores (a) are hauled from the mining pit to a dump (b), where they are sprayed with a water solution (c). The influent solution, aided by the growth of sulfur- and metal-oxidizing bacteria, leaches metal salts from the ore. The salt-rich leachate is collected in an effluent pond (d) and either recycled immediately (e) to pick up more of the metal-containing salts or pumped (f) to the processing plant for removal of the metal.

Heap leaching: This operation is identical in principle to the dump process but employs crushed, medium-grade ores piled on an impermeable basin from which the leachate is recovered, the solute is removed from it, and the leachate is concentrated and recycled (see fig. 31). This leaching operation is usually completed in a matter of months. To encourage the desired aerobic state, aeration tunnels are generally installed.

Figure 31

Heap Leaching Operation at the Gold Quarry Mine in Northeast Nevada

In this operation, a solution containing 125 ppm sodium cyanide is sprayed on the ore heap. The solution percolates down through the ore, dissolving gold from it. The gold-enriched percolate is then trapped by a plastic sheet, which channels the solution to a collecting pond, where it is pumped to the plant for removal of the gold and recycling of the solution.

The sodium cyanide heap leaching process is used on ores having an average gold concentration of 0.03 ounce/ton (0.9 ppm) and is economically attractive down to 0.01 ounce/ton (0.3 ppm). The mine shown is the largest gold leaching operation in the world.

This process does not use bacteria. However, somewhat analogous processes use bacteria in acidic solutions to extract copper from sulfide ores in heap or dump operations.

Courtesy of Komar Kawatra, Michigan Technological University, and Leonard Kroc, Newmont Gold Company

Vat leaching: Vat leaching is a purely chemical process by which concentrates of copper oxide ores are extracted by agitation with measured volumes of sulfuric acid. Research indicates that sulfidic ores can be extracted economically by the vat process using bacterial leaching (Brierley 1982, Torma and Banhegyi 1984).

In situ leaching: In selected mining sites that are inaccessible or abandoned because the high-grade ore has been recovered, acid leaching solutions are applied directly to either shallow or deep deposits and the leachates subsequently collected via wells. The process is confined to copper and uranium ores. Naturally occurring bacteria may augment this chemical process. It has been speculated that populations of appropriate thiobacilli and other sulfur-oxidizing bacteria could be injected into the locus to hasten and enhance the extraction. However, such a method is beset with difficulties, largely because the pathway of percolation is impossible to predict or control, thus endangering the quality of ground and surface waters. On the waterless Moon, the pollution of ground waters would not be a problem, but the extravagant use of water transported from Earth would be prohibitive.

In my opinion the only beneficiation operation having any potential for application on the Moon, or other space body, would be microbe-enhanced vat leaching, inasmuch as the bacteria must be provided with a confined, minimally sized Earth-like environment, as I have indicated. The oxygen for the bioprocessing unit would come from the reductive chemical processing of ilmenite, or other oxide ore, via electrolyzed water resulting from the reaction. Thus, chemical processing of lunar ores (or some other local means of producing oxygen) must precede any biobeneficiation for it to be economical. It seems unlikely that bioprocessing of ores would ever become a part of a closed or semi-closed regenerative ecological system unless the chemical beneficiation process proved to be ineffective (an unlikely prospect) and oxygen from eucaryotic photosynthesis could be spared for the bacterial processing of ores. Most likely, if cost-benefit analysis indicated any virtue to bioprocessing, the operation would be conducted outside of any human settlement and tended either by robots or humans in suitable "space suits."

Other Microbial Transformations of Metals

Anaerobic (Reducing) Conditions

In the absence of molecular oxygen, anaerobic or facultatively anaerobic bacteria are able to reduce sulfur or metals leading to the formation of sulfidic ores and reduced forms of iron, copper, and other metals.

Sulfate-reducing bacteria: Two large groups of chemosynthetic, heterotrophic bacteria are able to oxidize certain organic acids and utilize sulfate, sulfur in other oxidized states, and elemental sulfur as electron acceptors. These bacteria, classified in such genera as *Desulfovibrio, Desulfotomaculum*, and *Desulfuromonas*, are found in anaerobic aquatic habitats containing the various oxidized states of sulfur, which are reduced to hydrogen sulfide, thus leading to the deposition of sulfidic ores.

Photosynthetic bacteria: Among the photosynthetic bacteria are two groups that utilize hydrogen sulfide under anaerobic conditions as a source of electrons in reducing carbon dioxide:

$$CO_2 + 2\,H_2S \longrightarrow CH_2O + H_2O + 2\,S^0 \quad (12)$$

In one group, the "purple sulfur bacteria," the sulfur is deposited intracellularly. In another group, the "green sulfur bacteria," the sulfur is deposited outside the bacterial cell and subsequently oxidized to sulfate in the presence of hydrogen gas (source of electrons). These, and other photosynthetic bacteria, are anaerobic and thus unable to utilize oxygen as the final electron acceptor. The purple sulfur bacteria comprise ten genera (e.g., *Thiospirillum, Thiocystis*, and *Amoebobacter*); the green sulfur bacteria comprise four genera (e.g., *Chlorobium* and *Pelodictyon*).

Bacterial reduction of metal ions: Some strains of members of the genera *Thiobacillus* and *Sulfolobus* are able to reduce Fe^{+++} to Fe^{++}, obtaining reducing power from elemental or reduced sulfur, which is oxidized in the process. A number of other soil bacteria are able to reduce ferric iron as well. Manganese is both reduced and oxidized by various marine and soil bacteria. Ferromanganese nodules found in the oceans are laid down slowly through the bacterial reduction and oxidation of ferric and manganese ions (Summers and Silver 1978, Ehrlich 1981, Ehrlich and Holmes 1986).

Biotransformations of Some Toxic Metals and Metalloids

Within any land or aquatic ecosystem, toxic and nontoxic cations, whether naturally or artificially introduced, may be absorbed and metabolized by certain species among the indigenous microflora. In the process, inherent toxicities are often neutralized or modified. An excellent case in point is mercury which is highly toxic (binds sulfhydryl groups) as Hg^{++} but is enzymatically reduced by various mercury-resistant microorganisms to its volatile and nontoxic state as Hg^0 (Belliveau et al. 1987, Decker 1986, Hutchins et al. 1986, Thompson 1986).

Likewise certain toxic metals are methylated through the action of methylcobalamin excreted by a number of different aquatic and soil bacteria. This methylation does not necessarily detoxify the metal. In the case of mercury, the methyl and dimethyl forms can subsequently be concentrated in certain organisms, especially fish. Other metals that can be methylated by bacteria include tin, cadmium, lead, and arsenic.

Some bacteria can cleave certain organic mercurials into Hg^{++} plus an organic residue. Arsenic as As^{3+} can be oxidized by a number of bacteria to As^{5+}; in either state of oxidation, arsenic is toxic, but far less so in the pentavalent state. Reduced arsenic reacts with sulfhydryl groups; oxidized arsenic simulates phosphate in metabolic pathways. As oxoanions, tellurium and selenium are toxic to many bacteria. Some bacteria are able to reduce these salts to Te^0 or Se^0, thereby destroying their toxicity.

Since lunar rock contains virtually the same spectrum of toxic metals as found on the Earth (Morris et al. 1983), the biobeneficiation of ores on the Moon could be compromised by the presence of toxic cations in ore slurries, unless the bacteria introduced into the vats are resistant to high levels of cations of the more abundant toxic metals, including those to be recovered. Resistance to toxic metals is genetically endowed and can be introduced through gene recombination techniques in at least some of the bacterial species involved in the beneficiation of ores or in the removal of toxic cations from an aquatic environment (Belliveau et al. 1987, Ehrlich and Holmes 1986, Hughes and Poole 1989, Hutchins et al. 1986, Nicolaidis 1987, Pooley 1982, Torma 1987a, Trevors 1987, Tsezos 1985, Woods and Rawlings 1985).

Leaching of Ores by Growth of Heterotrophic Microorganisms

Sometimes sufficient organic matter is found in ores to support the growth of diverse microbes, resulting in the production of organic acids (e.g., lactic, citric, acetic, glutamic, and glycolic) which lower the pH, helping to solubilize the metals and encouraging the development of an acidophilic microflora of thiobacilli. This may be viewed as a synergistic effect.

On the other hand, alkaline leaching may be encouraged in the presence of organic nitrogen (protein, amino acids, purines, pyrimidines, etc.) as a result of deaminations catalyzed by heterotrophs, yielding ammonia which, in aqueous solution, becomes ammonium hydroxide. Some metals, notably copper, cobalt, and zinc, are compounded by ammonium hydroxide.

Calculations suggest it is not feasible to harness heterotrophs for the leaching of ores. Enormous quantities of decomposable organic matter would need to be provided in order for either acid or alkaline leaching to function at a commercial level (Kelly, Norris, and Brierley 1979). The use of organic wastes from sewage treatment plants has been investigated (Hutchins et al. 1986).

Bioaccumulation of Metals

Some microorganisms are capable of assimilating large amounts of metals from solution. The outlook for exploitation of such organisms for the removal of toxic ions or for the concentration of useful metals is very bright indeed (Ehrlich and Holmes 1986, Hughes and Poole 1989, Torma 1987a and b, Volesky 1987). Of course, all living creatures require certain trace elements which are found in low concentrations within all cells, though they would be toxic in higher concentrations. Certain microorganisms, however, are endowed with the capacity to assimilate large amounts of certain metals, even toxic ones.

Electrostatic Attraction

A variety of functional groups, or ligands, on cell surfaces carry positive or negative charges, conveying a net charge to the cell. Other things being equal, the intensity and sign (+ or –) of the charge depends on the pH of the extracellular environment. In most natural environments the pH is higher than the cell's isoelectric point; therefore, the cell will have a net negative charge and will passively attract cations, much like an ion exchange resin. However, there is some selectivity, suggesting the existence of specific binding sites for particular cations on the various surface structures. Certain fungi and bacteria, for example, bind large quantities of uranium ions, in some instances to the extent of 15 percent of the cells' dry weight. A yeast was found to bind mercury to its cell walls in amounts equivalent to the weight of the cell walls themselves. Certain species of algae and fungi concentrate copper to the extent of 12 percent of the cells' dry weight. Other metals bound by electrostatic attraction include Fe, La, Cd, Ca, Mg, Pb, Ni, Mn, Zn, Ag, K, and Na.

Surface Deposition or Precipitation (Biosorption)

Massive amounts of metals or insoluble metal compounds can be deposited on the surfaces of some microorganisms. This deposition will occur in some instances when the metal is metabolized; in other instances no transformation of the metal is required for its deposition (Belliveau et al. 1987, Ehrlich and Holmes 1986, Olson and Kelly 1986, Thompson 1986).

Those species of bacteria that reduce tellurite or selenite to metallic Te or Se deposit the metals on their surfaces, accumulate them intracellularly, or both. Some bacteria will aggregate insoluble lead compounds on their surfaces. Most common is the precipitation of ferric compounds and manganic oxides. While many bacteria can oxidize the manganous ion, sheathed, filamentous bacteria in the genera *Hyphomicrobium* and *Metallogenium* and in the *Sphaerotilus-Leptothrix* group become heavily coated with manganic oxides. Also, *Sphaerotilus-Leptothrix* and a group of stalked bacteria in the genus *Gallionella* acquire heavy deposits of oxidized iron, largely ferric hydroxide. Apparently, gallionellae derive energy through the oxidation of Fe^{++}, while the sheathed, filamentous group merely attract the insoluble ferric hydroxide to their sheaths. The genus *Zoogloea*, which is common in activated sludge sewage operation systems, produces copious quantities of polysaccharide slime having high affinity for Cu^{++}, Cd^{++}, Co^{++}, Ni^{++}, Zn^{++}, and Fe^{+++} (Hutchins et al. 1986). The production of extracellular polysaccharide slimes is common to many bacteria; chemically, they vary considerably from species to species, even from strain to strain (Ehrlich and Holmes 1986, Thompson 1986, Torma 1987a, Volesky 1987).

Intracellular Transport of Ions

Both monovalent (Na^{+}, K^{+}, Cs^{+}, Li^{+}, Tl^{+}, and NH_4^{+}) and divalent cations are specifically transported to satisfy nutritional needs of microorganisms. In some cases, rather high intracellular concentrations of certain metals are achieved. Often, the same transport mechanism will function for several cations; e.g., Mg^{++}, Co^{++}, Mn^{++}, Ni^{++}, and Zn^{++} in *Escherichia coli*. Others are more specific, although in all such systems various other cations will compete with a particular cation for uptake, in some cases even inducing efflux of ions. Fungi appear to concentrate metals or metalloids to a somewhat greater extent than do most bacteria (Hutchins et al. 1986, Summers and Silver 1978, Tsezos 1985).

Many of the metal ions are toxic, although the toxicity varies considerably from species to species (Belliveau et al. 1987, Ehrlich 1981, Summers and Silver 1978). Sometimes the inhibition of bacterial growth is synergistic. For example, *Klebsiella aerogenes* has been shown to be inhibited to a greater extent by Cd and Zn than by the sum of the individual toxicities of the two cations. The presence of clays, certain anions, and organic matter of various kinds often markedly reduces metal toxicity. Not surprisingly, metal chelators (e.g., ethylenediamine tetraacetic acid and citric acid) suppress the toxicity of many cations toward microorganisms. Clearly, toxicity is an important consideration in harnessing microbial cells to concentrate metals or metalloids.

An interesting case is found with the diatoms, which encase themselves in siliceous shells in an amazing variety of beautiful shapes. The uptake of silicates by diatoms has been shown to be competitively inhibited by germanic acid, thereby suggesting a means of recovering germanium from natural sources (Kelly, Norris, and Brierley 1979; Krumbein 1983). (See below for another aspect of silicate uptake.) Incidentally, the Russians for over 20 years have referred to "silicate bacteria," which they claim, in English abstracts, will free silicates from aluminosilicate ores, thereby beneficiating aluminum oxide (Alexandrov, Ternovskaya, and Blagodyr 1967; Andreev, Lycheva, and Segodina 1979; Andreev, Pol'kin, and Lyubarskaya 1982; Rohatgi, Trivedi, and Rohatgi 1984).

Not to be overlooked is the uptake of oxoanions, especially sulfate, the transport of which has been shown in *Salmonella typhimurium* to be competitively inhibited by chromate, selenite, molybdate, tungstate, and vanodate (descending order of effectiveness).

Natural Chelators

Some naturally occurring, low molecular weight compounds (citric acid, aspartic acid, and a number of dicarboxylic acids) have long been known to chelate various metal ions. Many microorganisms produce organic compounds that can do the same thing. Such organic compounds are collectively called "ionophores," the best known of which are siderophores (iron-attractors) (Nielands 1981; Brock, Smith, and Madigan 1984). Microbes that produce siderophores are believed to have evolved as the rising oxygen content of the Earth's atmosphere caused oxidation of much of the iron into its insoluble oxide and hydroxide states. To capture the minute quantities of free ferric ions that exist, microbes capable of synthesizing chelators of ferric iron arose. Incidentally, animals (including humans) trap iron through iron-binding proteins such as lactoferrin, transferrin, and ferridoxin, the latter being particularly abundant in the liver. Many pathogenic bacteria and fungi compete with the infected host for iron through the formation of siderophores. The siderophores—phenolates, hydroxamates, or cyclic peptides—are capable of binding ferric iron, which is subsequently transported into the cell, released, reduced enzymatically, and secreted back into the environment for recycling.

Recently, an ionophore for silicate, another ion very sparingly available, has been found in diatoms (Bhattacharyya and Volcani 1983).

Other metal-binding organic molecules, not chelators, abound in living systems. Of particular note is metallothionein, which binds a variety of cations by virtue of its available sulfhydryl (-SH) groups (Kägi and Kojima 1987).

Conclusion

As I emphasized in my introduction, the rigors of the Moon, or other space environments (asteroids, Mars, Phobos, Deimos, a station orbiting the Earth) are inimical to terrestrial life forms, including, of course, microorganisms. While it would be a far simpler matter to provide, on the Moon for example, conditions conducive to microbial existence than those conducive to human life, no ore could be beneficiated by bacteria there without the provision of a gas-tight container affording certain minimal conditions. No doubt the partial pressures of O_2, N_2, and CO_2 could be held to levels substantially lower than those found on the Earth—how much lower would have to be determined experimentally. The water supply would need to be adequate and continuous. Full radiation protection would be necessary, and temperature fluctuations would need to be minimized. It might well be best to select thermophilic bacteria for this endeavor.

Once a biobeneficiation reactor was constructed and all support systems were activated, it would be inoculated with appropriate strains of bacteria. More than likely, lyophilized (freeze-dried) cultures, probably of genetically engineered strains, would be reconstituted onsite in an aqueous solution, containing a mixture of nutrients brought from Earth as a dehydrated powder. The culture would be added to the moistened ore bed once the operator was satisfied that the cells were growing within the culture vessel. Initially, a leaching solution of dilute sulfuric acid would be added. The enclosure would have to be tight enough to retain all water vapors as well as the atmospheric gases.

As the size of the operation increased by expanding the size of the incubator, more water would need to be added. Unless sufficient sulfur or reduced sulfur in the ore was available for biological oxidation, additional sulfuric acid would be required. As the bacteria became established (as measured by the growth of a subculture or by microscopic examination of samples from the reactor or by chemical determination of the ratio of the concentrations of Fe^{+++} and Fe^{++}), further additions of the culture would become unnecessary. Before the biological operation was established, chemical reductive processing of oxide ores (e.g., ilmenite) would need to be functioning well to provide the necessary water and oxygen.

One problem with the foregoing scenario is that some of the minerals or elements in the ore might be toxic to the bacteria. Studies conducted more than 15 years ago revealed that lunar fines or their extracts inhibited as well as stimulated or proved innocuous to a variety of microorganisms (Silverman, Munoz, and Oyama 1971; Taylor et al. 1970; Taylor et al. 1971; Taylor and Wooley 1973). Silverman and colleagues found that, while the lunar substrate stimulated pigment production by the bacterium *Pseudomonas aeruginosa*, it inhibited pigment production by the bacterium *Serratia marcescens*. Others (Walkinshaw et al. 1970, Walkinshaw and Johnson 1971) found that lunar soil enhanced chlorophyll production and early development of ferns, bryophytes, and a number of seed plants. In keeping with these pioneering studies of the interplay between lunar materials and living organisms, I undertook to make a preliminary study (Johansson 1984) of the effects of leachates of lunar fines on the growth of the common colon bacillus, *Escherichia coli*, in a glucose medium with minimal mineral salts. I found that, depending on its concentration, the leachate either enhanced or inhibited the growth of the bacteria. The specific elements or minerals responsible for the various biological responses to the lunar materials have not been identified.

Prior terrestrial research would be necessary to provide guidance on dealing with a toxicity problem, if it could be identified in advance by appropriate tests of lunar materials. Means of dealing with such a problem could include the addition of hydrogen sulfide, chelators, or certain mineral salts known to block specific toxic ions. There is a vast literature on handling toxicity, but research specifically applied to lunar or asteroidal materials is needed.

Another biological approach to the problem of recovery of certain metals from lunar ores might be the application of metal-binding agents produced, at least initially, on Earth. Candidate substances include ionophores and metallothionein.

The introduction of the microorganisms needed for the bioprocessing of lunar ores would probably not be an early event in the establishment of an outpost on the Moon. If a human habitation with recycling (of water, oxygen, carbon dioxide, nitrogen, sulfur, and other essential nutrients) was established, the cultures needed in the mining operation would be useful as part of the microflora of that ecosystem. The thiobacilli and other bacteria involved in the leaching of ores are important in the cycles of sulfur, nitrogen (some fix N_2), carbon, and oxygen on Earth (see fig. 32).

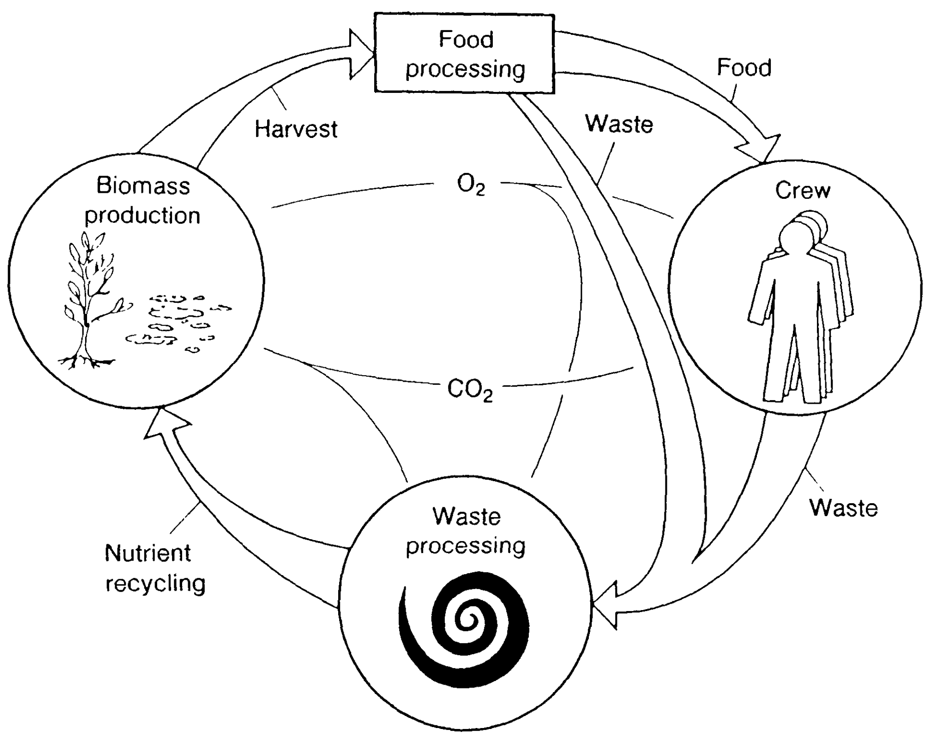


Figure 32

Regenerative Life Support System

In a controlled ecological life support system, as diagramed here, biological and physicochemical subsystems would produce plants for food and process solid, liquid, and gaseous wastes for reuse in the system

A bioprocessing unit, in which bacteria oxidize and catalyze the extraction of metals from their lunar or asteroidal ores, could be incorporated into this regenerative system. The bioprocessing unit would contribute to the gas and nutrient recycling, the biomass inventory, and the waste processing of the larger regenerative life support system.

One concern is the availability in the lunar soil of the sulfur needed for the ore-beneficiating bacteria to gain energy and by the same process to produce the sulfate for the acid leaching process. In this regard, carbonaceous chondritic asteroids might yield material more suitable for biological ore beneficiation than would the Moon. Of course, sulfur from the Earth could be added to the beneficiation enclosure on the Moon. A fringe benefit of using asteroidal material would be its content of organic matter, which desirable heterotrophic bacteria might possibly utilize for their carbon needs.

Another question that needs to be answered is whether the low level of nitrogen in the lunar regolith (Gibson 1975) is sufficient to enable significant bacterial colonization. It may be necessary to provide, at the onset, nitrogen in the form of nitrate. (Ammonium nitrogen would work but some of it would be oxidized to nitrate, thus imposing a demand on atmospheric oxygen.) The amount of phosphorus may also not be adequate for bacterial life on the Moon. These bacterial nutritional problems would also apply to the development of an ecosystem supporting human life.

In summary, bioprocessing using bacteria in closed reactors may be a viable option for the recovery of metals from the lunar regolith. Obviously, considerable research must be done to define the process, specify the appropriate bacteria, determine the necessary conditions and limitations, and evaluate the overall feasibility.

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Processing of Metal and Oxygen From Lunar Deposits

Constance F. Acton

Metallurgical Processing

Introduction

Metallurgy—the art and science of economically concentrating, extracting, refining, and fabricating metals and alloys—has existed on Earth from antiquity. Gold, silver, and copper—elements that can occur as metals in their natural state—were used as long as 10 000 years ago. Metals extraction technology can be traced back at least 6000 years. Recently, major advances have been made in metallurgical processing. This developed field may now be ready for application to the production of metals in space.

Table 11 shows the steps involved in the production of mineral-based materials for commerce.

TABLE 11. *Steps in the Production of Mineral-Based Materials for Commerce* [From Dresher 1974]

I	II	III	IV	V	VI
Exploration	Production of raw materials	Beneficiation of raw materials	Extraction and production of metals. Primary processing of minerals for nonmetallic uses. Processing and conversion of fuels.	Fabrication of materials with specific composition	Properties and uses of materials

Mineral science and technology (II–V)

Geological sciences (I)

Materials science (V–VI)

Metallurgical engineering:
Extractive (minerals-based) (III–IV) **Adaptive (metals-based)** (V–VI)

The first step is exploration to define potential sources of raw materials. The Apollo Program has defined some lunar resources; further exploration will undoubtedly find additional ones. Whether or not a metal-bearing deposit is classified as an ore, a reserve, or a resource is a question of economics. An ore is a resource that can be extracted at a profit. A reserve is a resource currently uneconomical to mine or greater than existing demand. A resource becomes a reserve or an ore if the proper technologies and economic conditions are developed.

The concentration of most metals in the crust of the Earth (or the Moon) is extremely low. And even the most abundant elements on Earth—iron, aluminum, silicon—cannot generally be extracted from common rock at a profit. A metal must be sufficiently concentrated in a mineral before it is mined. Then the useful constituents of an ore must be separated from the residue (gangue) by the process of beneficiation. In this process, the ore minerals are concentrated by physical separation, exploiting differences in such properties as particle size, shape, and size distribution; specific gravity; magnetism; and electrostatics.

The importance of the beneficiation step cannot be overemphasized. Only after the ore minerals have been concentrated can economical metal extraction take place. On the Moon, some whole rocks may be ores for abundant elements, such as oxygen, but beneficiation will be important if metallic elements are sought from raw lunar dirt.

In the extraction process, a beneficiated metallic ore, such as an oxide, sulfide, carbonate, or silicate mineral, is converted to the reduced metal. Such minerals are the stable forms of metals in the Earth's or the Moon's environment. In the case of the important iron ore mineral magnetite (Fe_3O_4), the free energy of formation at 0°C is more than 120 kcal/mole O_2 according to the reaction

$$3/2\ Fe + O_2 = 1/2\ Fe_3O_4$$

This explains the natural tendency of metallic iron to rust in air; that is, to convert to its thermodynamically stable oxide form. A very useful pictorial representation of the relative stability of metal oxides is an Ellingham diagram (fig. 33). These diagrams are also available for chlorides, fluorides, and sulfides.

Figure 33

Ellingham Diagram

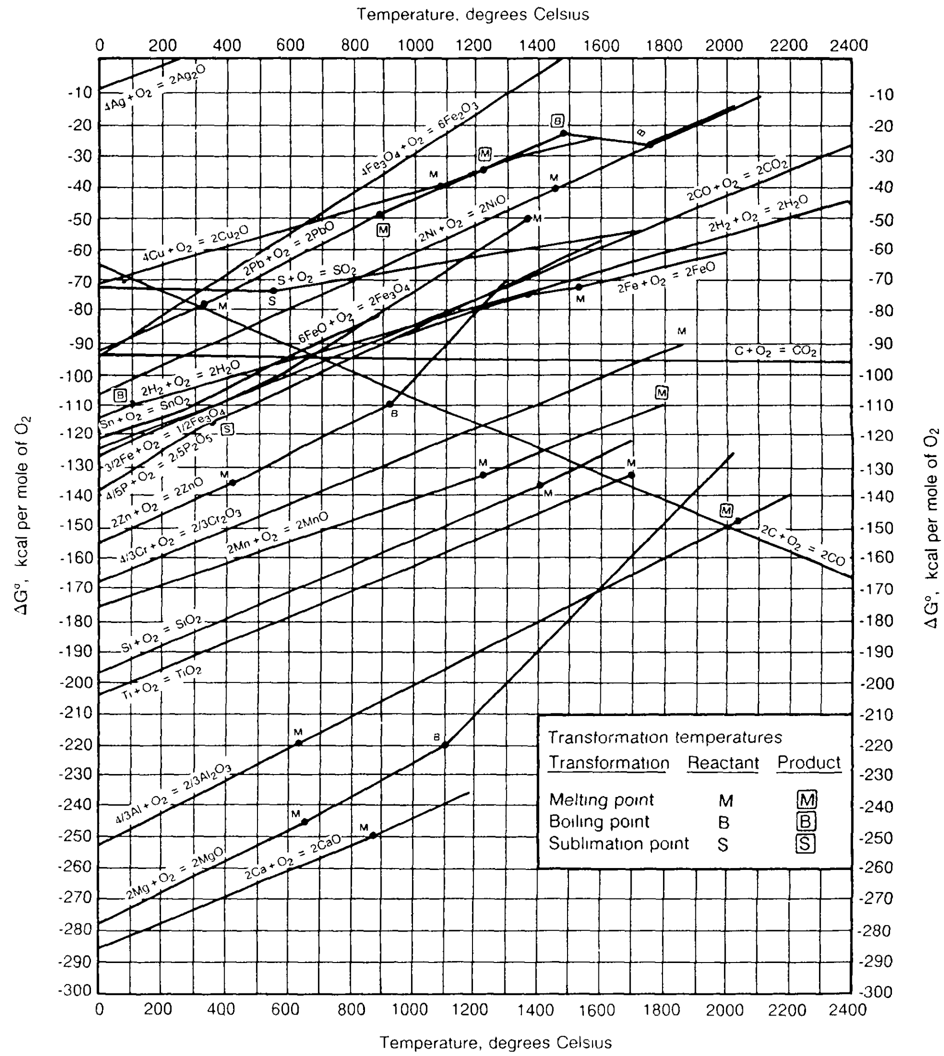
This diagram shows the standard free energy of formation of a number of oxides as a function of temperature. Accuracy varies between ±1 and ±10 kcal

At 25°C the oxides produced by these reactions form with these free energies:

(1)	$4Ag + O_2 = 2Ag_2O$	-5 18 kcal per mole of O_2
(2)	$2C + O_2 = 2CO$	-65 62
(3)	$4Cu + O_2 = 2Cu_2O$	-69 96
(4)	$S + O_2 = SO_2$	-71 79
(5)	$2Pb + O_2 = 2PbO$	-90 5
(6)	$4Fe_3O_4 + O_2 = 6Fe_2O_3$	-93
(7)	$C + O_2 = CO_2$	-94 26
(8)	$2Ni + O_2 = 2NiO_2$	-103 4
(9)	$2H_2 + O_2 = 2H_2O$	-116 42
(10)	$2Fe + O_2 = 2FeO$	-116 8
(11)	$3/2\ Fe + O_2 = 1/2\ Fe_3O_4$ ($3Fe + 2O_2 = Fe_3O_4$)	-121 2
(12)	$2CO + O_2 = 2CO_2$	-122 9
(13)	$Sn + O_2 = SnO_2$	-124 2
(14)	$6FeO + O_2 = 2Fe_3O_4$	-134 4
(15)	$4/5\ P + O_2 = 2/5\ P_2O_5$ ($4P + 5O_2 = 2P_2O_5$)	-146 1
(16)	$2Zn + O_2 = 2ZnO$	-152 1
(17)	$4/3\ Cr + O_2 = 2/3\ Cr_2O_3$ ($4Cr + 3O_2 = 2Cr_2O_3$)	-166 8
(18)	$2Mn + O_2 = 2MnO$	-173 6
(19)	$Si + O_2 = SiO_2$	-192 4
(20)	$Ti + O_2 = TiO_2$	-203 8
(21)	$4/3\ Al + O_2 = 2/3\ Al_2O_3$ ($4Al + 3O_2 = 2Al_2O_3$)	-251 18
(22)	$2Mg + O_2 = 2\ MgO$	-272 26
(23)	$2Ca + O_2 = 2CaO$	-288.8

The more energy is given off during the formation of an oxide, the more likely that oxide is to form and the more stable that oxide is. By the same token, the more negative the free energy of formation of an oxide, the harder it is to break that oxide down into the elemental metal and oxygen. Thus, the metals on the lower lines of this chart can reduce the metallic oxides on higher lines

After Richardson and Jeffes 1948.



The larger the negative free energy of formation, the more stable the oxide. It can readily be seen that at 0°C the relative stability for oxides increases from iron through silicon and titanium to aluminum. The metals in the more stable oxides (lower on the chart) can chemically reduce the metals in the less stable oxides (higher on the chart). Also shown are lines for carbon and hydrogen, common reductants used in terrestrial extractive metallurgy. The challenge is to find procedures to extract the element of interest economically.

In some terrestrial cases, metals may be economically extracted at a higher than normal rate of energy consumption per unit of metal produced because cheap electrical energy is available; for instance, siting an aluminum smelter near a hydroelectric supply. In such a case, the rate of energy consumption may be 10-50 percent more than the general industry practice. The economics of utilizing metals from resources in space are driven by transportation costs rather than energy costs. Many processes proposed for extraction of lunar materials are energy-intensive. Thus, the cost of energy on the Moon will be an important factor in developing processing technology. For example, concentrated solar heat will be cheaper than electricity and should be utilized where possible.

Geochemical Availability

Skinner (1976) has provided a lucid analysis of the geochemical availability of various elements on Earth. The basic concepts are directly applicable to the Moon. The most abundant metals in the Earth's crust are silicon, aluminum, iron, calcium, magnesium, sodium, potassium, and titanium (see table 12). For comparison, the composition of a typical lunar mare basalt [sample 10017, as analyzed by Wänke et al. (1970)] is also shown. To a first approximation, the compositions of terrestrial and lunar rocks are not too different.

TABLE 12. *Major Chemical Elements in the Earth's Crust and in a Typical Lunar Mare Basalt*

Element	Continental crust, weight %	Lunar sample 10017, weight %
Oxygen	45 20	40.7
Silicon	27.20	19.6
Aluminum	8 00	4.4
Iron	5.80	14.6
Calcium	5.06	8.2
Magnesium	2.77	4.8
Sodium	2 32	0.347
Potassium	1.68	0.206
Titanium	0.86	7.0
Hydrogen	0 14	---
Manganese	0 10	0.148
Phosphorus	0 10	---
Total	99 23	100.001

The geochemically scarce metals are those which do not normally form separate minerals but are present as substitutional atoms in common rock; for instance, lead or zinc may occur at ppm levels in orthoclase ($KAlSi_3O_8$). To release lead from the silicate structure, the entire mineral has to be chemically broken down, an extremely complex and energy-intensive process. "The mineralogical barrier" described by Skinner (see fig. 34) refers to the point at which the easily processed minerals, such as sulfides, are so rare that mineral beneficiation techniques cannot be applied economically. At this level, the increased energy required to extract trace metals from silicates must be expended. Although the diagram is conceptual, the energy jump for the mineralogical barrier is 2 to 3 orders of magnitude higher than the energy required for the processing of typical ore minerals on Earth.

On Earth, mainly by means of free water, nature has concentrated the rarer metals in ore deposits. Such deposits are unknown on the dry Moon. On the Moon, metallic iron can be concentrated from soils, and iron and titanium oxides (ilmenite) and iron sulfides (troilite) can be concentrated from soils or disaggregated rocks. Essentially all other known lunar ores are above the mineralogical barrier and will require considerable energy for their extraction. Examples include silicon and aluminum from anorthite and iron or magnesium from pyroxene.

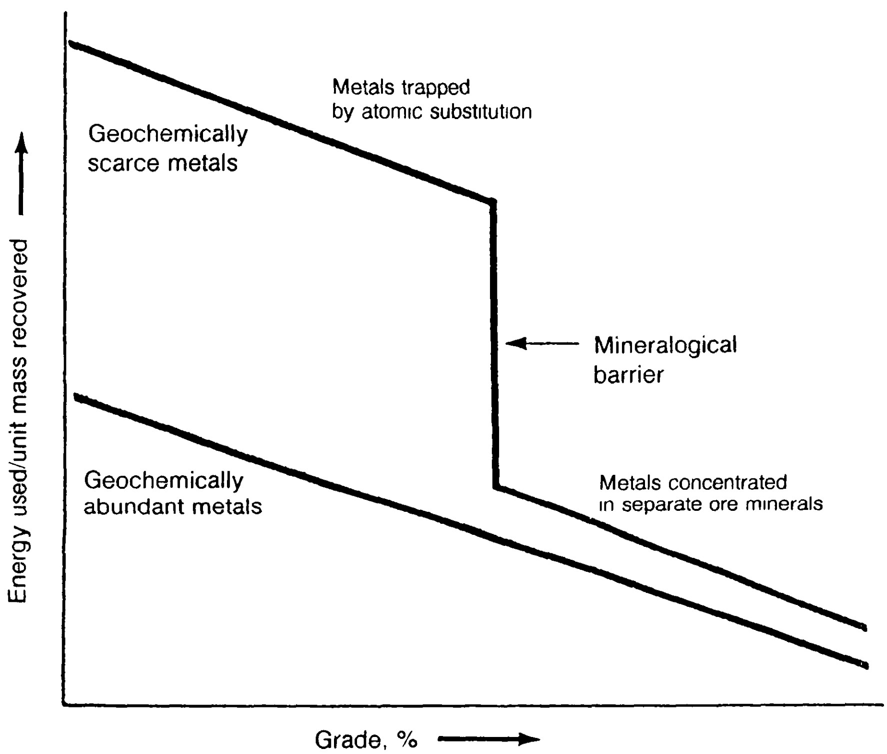


Figure 34

The Mineralogical Barrier

The relationship between the grade of an ore and the energy input per unit mass of metal recovered is shown for both scarce and abundant metals. A steadily rising amount of energy will be needed to produce even geochemically abundant metals from the leaner ores of the future, but the amount of energy needed to produce scarce metals will take a tremendous jump when the mineralogical barrier is reached. At that point, when ore deposits are worked out, mineral concentrating processes can no longer be applied, and the silicate minerals in common rocks must be broken down chemically to separate the atoms of scarce metals from all the other atoms.

From Skinner 1976

Extraction Technology

Extraction of various metals from mineral ores has developed into three subdisciplines: pyrometallurgy, electrometallurgy, and hydrometallurgy. In each subdiscipline, a different mechanism provides the driving force to reduce the combined metal to its elemental form.

In pyrometallurgy the force that drives the chemical reduction of a metal oxide is high temperature. For many of the less stable metal oxides, carbon reduction at elevated temperatures is possible. This technology has been used successfully for iron smelting. (See figure 35.) For the more stable metal oxides, such as TiO_2 and Al_2O_3, carbon reduction proceeds spontaneously (that is, the free energy becomes negative) only above 1630°C and 2000°C, respectively. The disadvantages of high temperature extraction include

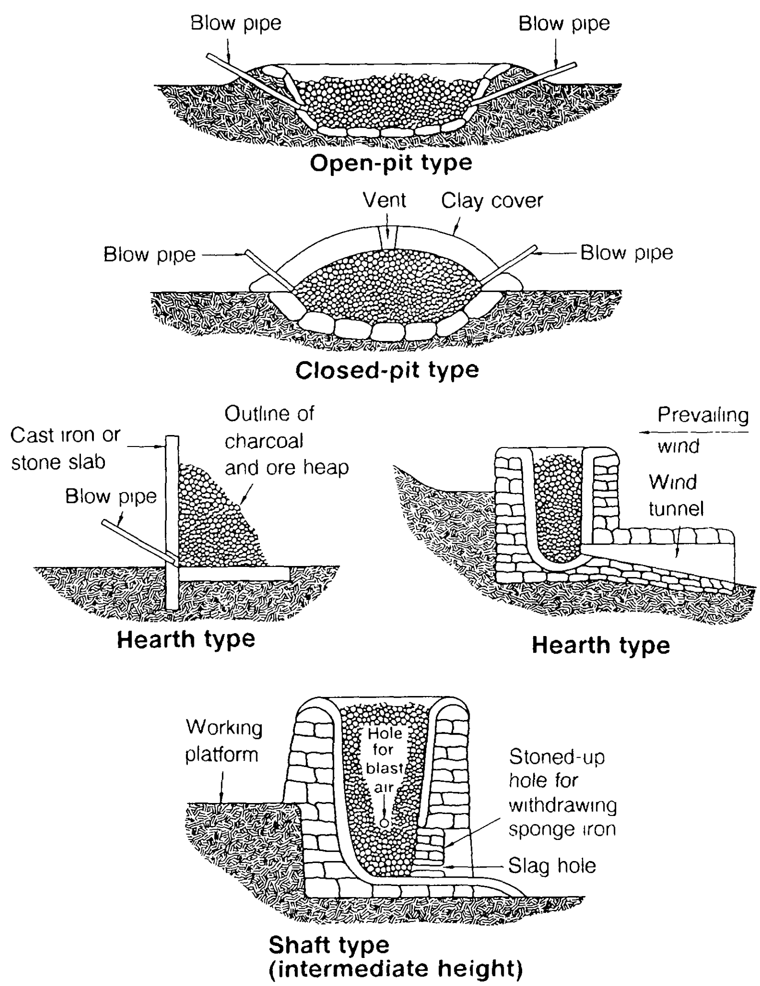


Figure 35

Iron Smelting

Iron smelting was discovered by ancient humans, changing the course of civilization. The basic process is one in which carbon (charcoal) is mixed intimately with iron oxide. Burning of the carbon produces carbon monoxide, which reacts with the iron oxide to produce metal and carbon dioxide, which is vented from the smelter. Many configurations were used in early smelters to optimize the delivery of oxygen and remove the metal and slag (residue) from the process. The slag consists primarily of impurities in the oxide ore.

Courtesy of the Association of Iron and Steel Engineers, reprinted from The Making, Shaping and Treating of Steel, *10th ed., fig. 1-2* the large amount of energy required for heating, the difficulty in finding suitable container materials, and the problem of reoxidation of the molten metal.

In electrometallurgy an electrical rather than a chemical driving force is used to reduce the metal oxide. An example of a well-developed electrometallurgical technology is the extraction of aluminum from Al_2O_3 by electrolysis in molten fluoride salts.

Hydrometallurgy exploits the fact that certain minerals are soluble in aqueous solutions such as sulfuric acid. Once dissolved, the metal ions can be recovered by low-temperature electrolysis, precipitation, chemical reduction, ion exchange, or solvent extraction. (See figure 36.)

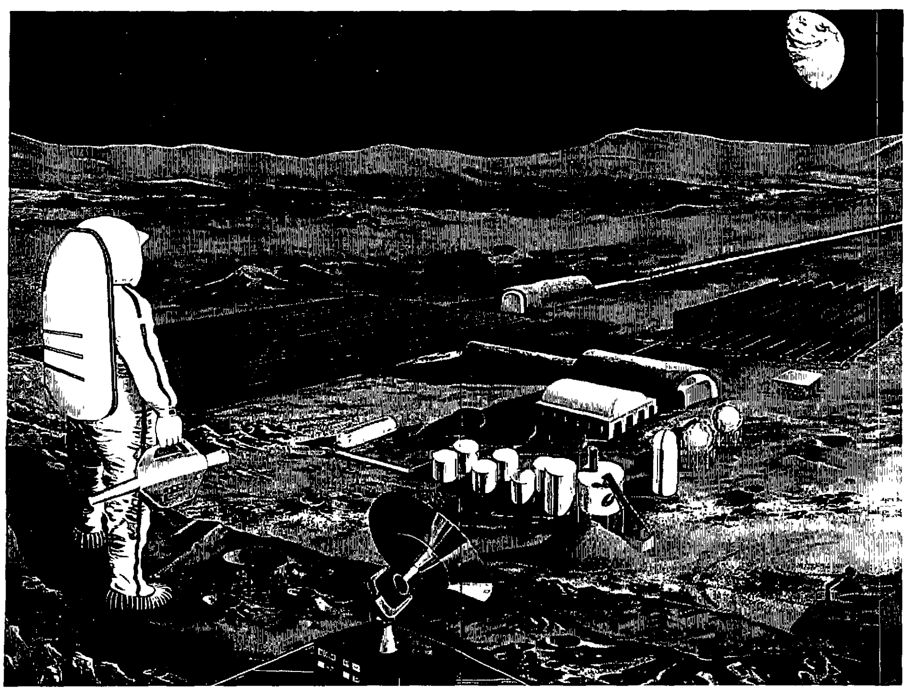


Figure 36

Chemical Extraction Plant on the Moon

In this artist's concept of a lunar chemical plant, metals and oxygen are extracted from lunar soil using relatively low-temperature aqueous chemistry. First, lunar soil and crushed rock are leached in aqueous hydrofluoric acid (HF) in the tank with the chute and chimney, making metal fluorides The metal fluorides in solution are further processed in the tall and short cylinders and then electrolyzed in the light-colored building with the pillars, producing oxygen and metals at the electrodes

Oxygen is liquefied and stored in the spherical tanks (two large ones and many small ones under a roof) The HF is recovered, recycled, and stored in the vertical cylinder on the right. The horizontal cylinder on the left holds the water needed for this aqueous process.

The upright panels in the background to the right radiate the excess heat generated by the process. The flat solar panels in the background to the left supply power to the electromagnetic launcher in the middle background, which will shoot lunar products to orbit. The soil-covered buildings in the middle provide workshops and housing for the lunar pioneers.

Artist: Scott Berry

Courtesy of William N Agosto, Lunar Industries, Inc

The scarcity of water and the abundance of solar energy available at nonterrestrial sites suggest that pyrometallurgy or electrometallurgy will be favoredas processing technologies there. Processes that conserve volatile substances by recycling will be essential to minimize the transport of makeup chemicals, as will be processes that limit the consumption of special materials, such as fluxes or anodic substances, which would have to be transported to space.

This discussion of geochemical availability and extractive metallurgy implies that extraction of minor elements in space is questionable unless specific natural concentrations are discovered or energy becomes very inexpensive. The relative costs of scarce and abundant metals will become even more disparate in the future on Earth as well as in space. It may be more cost-effective to substitute the lesser properties of an abundant metal like iron or aluminum than to attempt to extract a geochemically scarce metal. This line of thought suggests that effort be directed to extracting iron on the Moon rather than to recovering scarcer metals (such as those from the platinum group) from asteroids. When exploration and timing difficulties are added to the energy consumption considerations, the case for going after the rarer precious metals becomes yet weaker.

Proposed Extraction Schemes

Introduction

In the following section, a variety of plausible processing technologies are described. In general it may be said that these technologies are derived from a limited amount of terrestrial experience and are totally untested in application to the extraction of nonterrestrial resources. Work must be initiated in the near future to sort out these and other proposals, for it is the experience of the metallurgical industry that such processes require much development and testing, at bench-top and pilot-plant levels, before production facilities are achieved. Development times of 10 to 25 years have been experienced, and many false steps have been taken. For example, an Alcoa plant for extraction of aluminum metal from anorthite by carbochlorination and electrolysis of aluminum chloride was constructed at a cost of $25 million, only to be shut down after a short operating time because of technical problems.

Many process schemes have been proposed for recovering a variety of metal products and volatiles from a variety of lunar feedstocks. A collection of pyrometallurgical, electrometallurgical, and hydrometallurgical approaches have been proposed, with varying amounts of research and engineering data to support them.

The participants in this study looked at scenarios for the development of space resources in the next 25 years. The materials subgroup of study participants reached the consensus that, within this timeframe, oxygen production from lunar resources will be the major objective of the space program. The participants also assessed what metals recovery technologies can be implemented and suggested what time would be required to develop more complex metal processing technologies.

Recovery of Meteoritic Iron

History and thermodynamics teach us that the most appropriate metal to recover first is iron. The most basic approach to recovering iron on the Moon is to process the meteoritic iron found in lunar soils. Small chunks of meteoritic iron have been found in lunar samples, but most metal exists in the form of micron-size particles, particles encapsulated by or attached to silicates or glasses.

The first processing effort should be to concentrate this elemental iron by mineral beneficiation techniques (such as magnetic separation). Current knowledge does not suggest that regions of elevated metal content can be found, but additional information on the abundance and ease of separation of the metal is needed. In addition, trace elements in the iron must be identified. Alloying elements or solutes can have a profound effect on the iron's mechanical properties. The iron and steel industry has probably never looked at iron alloys of lunar composition, because carbon and other solutes are always introduced in the smelting process.

The utilization of meteoritic iron is suggested as a first approach because it does not require the energy-intensive and chemically complex step of extraction. However, a process for separating the metal from adhering silicate minerals must be developed. The recovered lunar iron can either be processed directly into parts by powder metallurgical techniques or be melted at about 1550°C and cast into ingots for wrought products.

Even though this is the simplest process for producing lunar iron and the technologies for beneficiation, melting, and pressing or casting and forming are fairly well developed on Earth, the application of these technologies in the lunar environment will present many challenges.

Processing of Lunar Ilmenite

The next simplest process for recovering iron is to reduce it from ilmenite ($FeTiO_3$). For the reaction

$$FeTiO_3 + H_2 = Fe^0 + TiO_2 + H_2O$$

the free energy at 1000°C is 5.86 kcal/mole. This gives a very low equilibrium constant $K_c = 0.103$ at 1000°C. Thus, the reduction of ilmenite to reduced iron plus TiO_2 is not strongly favored thermodynamically and may not proceed to completion. Furthermore, the reaction will not proceed to the right unless H_2O (g) is removed from the system. Thus, if thermodynamically favorable, the rate of reaction must be determined.

Another ilmenite reduction scheme based on a commercial process has been suggested for the Moon (Rao et al. 1979). In it the ilmenite is reacted with carbon to reduce FeO to Fe^0. The iron from the ilmenite is chlorinated at 800°C in a fluidized bed reactor while the TiO_2 remains unchanged. The $FeCl_3$ gas is condensed and could be reacted with oxygen gas at 300-350°C in a second fluidized bed to produce Fe_2O_3. The Fe_2O_3 could then be reduced with either carbon or hydrogen gas below 1000°C to produce low-carbon steel or iron. The CO or H_2O formed would be recycled to recover the oxygen. Alternatively, the $FeCl_3$ could be reduced directly to metallic iron with hydrogen at 700°C. The hydrogen chloride formed as a byproduct would be recycled. The flow diagram for this conceptual process is shown in figure 37.

The residue in this process is TiO_2, which can be further processed to recover titanium metal. Since titanium forms a highly stable oxide, it cannot be reduced with carbon or hydrogen. It can, however, be reduced with calcium metal. A process has been developed to perform this reduction by pelletizing TiO_2 and calcium metal powders and heating at 925-950°C for several hours. The CaO is then preferentially dissolved by acid leaching. Disadvantages here are that the acid and water must be recycled and that water is not available at the site. Calcium metal could be provided from processing of anorthite for aluminum.

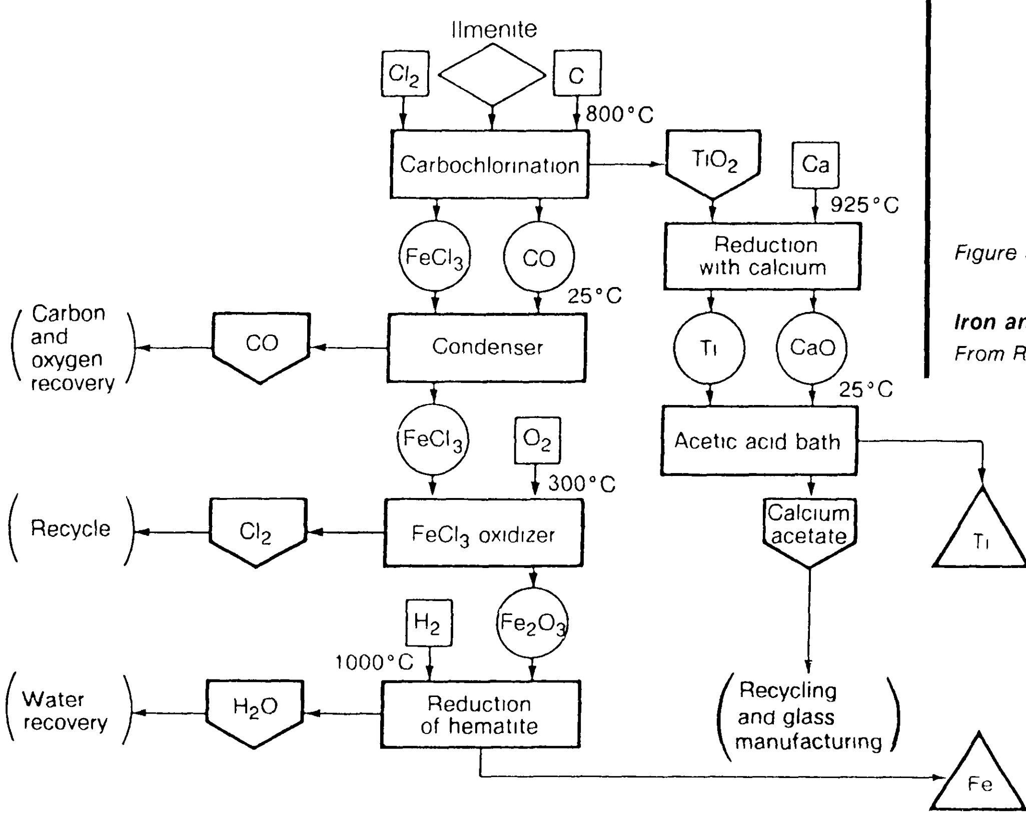


Figure 37

Iron and Titanium Processing

From Rao et al. 1979.

The most likely end product of ilmenite processing is a partially reduced mixture of Fe, FeO, TiO_2, and other impurities. There are several possible options for using this type of product.

The simplest is not to try to recover the iron but rather to use the material as is to form "cermet" blocks for construction. Assuming that 50- to 200-µm particles are produced from the fluidized bed reactor, sintering may be successful at temperatures just below the melting point of iron. To evaluate this option further, considerable test work on pressing (using, for example, a hot isostatic press) should be done on simulated residues. If this option proves unsuccessful, the iron-titania residue may simply be stockpiled until such time as more advanced processing technology is developed for the lunar site.

If iron recovery is required and the chlorination process does not prove feasible, simply melting the iron out of the residue may successfully produce a crude iron alloy suitable for structural uses. Alternatively, a low-temperature carbonyl process could be utilized to extract the iron.

Other Proposed Processes

For lunar processes to be successfully developed, certain guidelines must be kept in mind. These include the following:

- Pyrometallurgical and electrometallurgical operations are favored. Because of the lack of available water on the Moon, hydrometallurgical operations will require additional development to recover process water with high efficiency.

- Reductants such as chlorine, hydrogen, and carbon, if not obtainable from lunar sources, must be brought from Earth and therefore should be recycled to minimize their resupply.

- The processes should be tailored for the high-vacuum, low-gravity space environment. Alternatively, methods for providing inexpensive pressurized volumes would have to be developed.

- The oxygen produced in the metal recovery process will be more important than the metal recovered, at least in the early phases.

The NASA SP-428 paper (Rao et al. 1979) was written by recognized metallurgical experts who did a competent job of assessing the available thermodynamic and kinetic literature for several aluminum, titanium, iron, magnesium, and oxygen extraction processes. Their analysis of the research done and needed may stand up to scientific scrutiny by their peers. None of their candidate processes, however, has been sufficiently tested to provide the data needed for process plant design by a competent engineering company.

A number of other processes have been referred to at this workshop. These include acid leaching, alkali leaching, fluorination, electrolysis, basalt vaporization, plasma smelting, and sulfide processing. Some of these processes can be summarily dismissed for such reasons as requiring large amounts of water or of a nonlunar reductant, impracticality of recycling, or requiring extraordinary amounts of energy. For those few which may warrant less cursory evaluation, the basic scientific data have not yet been provided.

Process Development

What is needed *at a minimum* to establish credibility in the scientific community is compelling thermodynamic and kinetic data for any proposed system.

Before any research work can begin, it is obvious that a comprehensive literature review must be done. Any pertinent thermodynamic data must be critically evaluated. The feed material must be realistically characterized in terms of physical and chemical properties. The stoichiometry and phase relations for the system must be known.

The thermodynamic properties of the system should be determined experimentally. The extent of deviation from calculated thermodynamic values for condensed and vapor phases should be measured. Appropriate phase diagrams should be constructed relating phase composition, free energy of formation, and temperature; e.g., phase diagrams for the elements in the ilmenite (Fe-Ti-O) and for the products of the ilmenite reduction process (Fe-Ti-O_2-H_2) for temperatures between 700 and 1000°C. The vapor phase and residue should be accurately analyzed as well.

If the thermodynamic data indicate an attractive extraction process, the kinetics and heat and mass transfer properties must next be systematically investigated.

It should be noted that experimental programs for high-temperature processes are extremely difficult and may require several years' effort.

Assuming that the proposed process has been demonstrated by such a bench-scale program to be feasible, it is appropriate before proceeding further to do an economic evaluation of the process. Operating and capital costs should be assessed, and special considerations, such as mass and energy requirements, need to be carefully analyzed.

If the process still appears attractive, then a terrestrial pilot plant is mandatory. If the process does not work on Earth, it probably cannot be made to work on the Moon. A great deal of consideration would have to go into designing a pilot plant that would yield useful information regarding a plant at a nonterrestrial site. Even for the very simplest of processes, it is clear that its development for use on the Moon would require an intensive research and development program. If begun now, the most optimistic program for an ideal process would probably take 20-50 years and involve hundreds of millions of dollars.

Thus, if lunar resources are to be used in the early 21st century, there is a clear need to begin a research and development program now. It should proceed through the stages presented in table 13.

TABLE 13. *Research and Development Program for a Lunar Metal Recovery Process*

Stage	Time	Personnel	Cost	Comments
1. Technology review	6 months	Metallurgical specialists	Modest	
2. Experimental research	3-5 years	Researchers at several institutions concurrently	Considerable	Although iron, aluminum, silicon, and titanium should all be evaluated, priority should be given to iron, which is thermodynamically the least stable oxide and the metal with the largest body of known technology
3. Pilot plant	2 years or more	R&D engineers	Significant	
4. Plant design	2-3 years	Engineering and construction team	Unknown until phases 2 and 3 are completed	All of the process technology developed would be translated into hardware amenable to lunar operation.
5. Hardware construction	3-5 years	Manufacturing and construction personnel	Unknown until phase 4 is completed	Hardware could be constructed on Earth or on the Moon or both.
6. Plant startup	1-2 years	Engineering and construction team	Unknown until phase 4 is completed	

A fair amount of speculation on metal recovery processes has been made, but so far little of the work can stand up to scientific scrutiny. To build a workable lunar materials recovery plant, the logical program described must be followed. Sufficient amounts of capital and work time by qualified metallurgical personnel must be provided.

Experts in the fields of mineral science and metallurgy must contribute to the development of the required new process technology. The most effective means of achieving this objective is by joint cooperative efforts between established metallurgical experts and specialists in the planetary sciences. If the space program attempts to develop metallurgical capabilities in-house, the timing objectives for the new technology will be impossible to meet.

Applicability of Space Technology to Terrestrial Metal Processing

Metallurgical technology on Earth has developed slowly with a limited base of trained technologists and R&D funding. The research is very difficult experimentally, complex, and hard to scale up. Hence, process development is slow.

It seems obvious that even a minor R&D effort by the space program would be a major contribution to the existing bodyof knowledge. Although it is impossible at this time to judge what metal processing technologies will be developed for space in the next 25 years, it is of interest to use some general guidelines to speculate, as follows.

Chloride and fluoride systems offer interesting potential for metal extraction. Such processing schemes would provide a technology base for a terrestrial metallurgical breakthrough that would reduce energy consumption per unit output. Along with the process chemistry, the development of recycling technology could clearly be advantageous in dealing on Earth with ever increasing environmental limitations.

Development of electrochemical, electrode, or electrolysis technologies for metal extraction, refining, or processing could advance the currently rather empirical state of the art on Earth for certain metals.

The development of a computer interface with metallurgical process technology would likely advance the state of metallurgy by several orders of magnitude and is one of the most exciting prospects for change.

Metals produced by new technology on the Moon will not contain the solutes usually contained in their counterparts on Earth, such as carbon and sulfur in steel. Physical and mechanical properties of a whole new cadre of alloys will be measured. The creation of such uncontaminated alloys will advance the field of materials science since the effect of impurities on properties can be zeroed out. Such new alloys may be used on Earth for unique applications, now impossible to fulfill.

And new metallurgical technology developed to extract metals from alternate mineral feedstocks could have strategic and possibly commercial value on Earth.

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Concrete: Potential Material for Space Station

T. D. Lin

Introduction

To build a permanent orbiting space station in the next decade is NASA's most challenging and exciting undertaking. The space station will serve as a center for a vast number of scientific projects. Because of high launch costs, aluminum and fibrous composite materials, light and strong in nature, are being considered for the construction. To my knowledge, concrete has been totally neglected in the search for suitable materials.

In 1981, Construction Technology Laboratories, a division of the Portland Cement Association, initiated a study of the feasibility of using concrete for structural components of a space station. The idea of using concrete in space may seem absurd to many scientists and engineers. Nevertheless, the study shows that concrete is not only suitable but also economical for space station construction.

Concrete

Concrete is basically a mixture of two components: aggregate and cement paste. The paste, composed of Portland cement and water, binds the aggregate into a rocklike mass as it hardens. In general, concrete consists of three parts aggregate and one part paste by weight.

Since the invention of Portland cement in 1824, concrete has been a widely used construction material and a popular subject for study by the engineering community. Using current concrete technology, a compressive strength of 6000 psi [41.4 megapascals (MN/m^2)] can easily be attained with the proper mix design. Concrete made with superplasticizer has a strength of 10 000 psi (69 MN/m^2), and treatment of superplasticized concrete with silica fume (Malhotra and Carette 1983) raises its strength to 17 000 psi (117 MN/m^2).

Reinforced Concrete

The flexural strength of plain concrete is generally low, about 1/10 its compressive strength. However, concrete reinforced with steel rods has found common use in the construction of high-rise buildings, nuclear containment structures, and pressurized liquid nitrogen tanks. The strength design method recommended by the Building Code Requirements for Reinforced Concrete (ACI 318-83) assumes that the concrete takes up the compressive stresses and the reinforcing steel takes up the tensile stresses.

Concrete reinforced with either steel or glass fibers has greatly increased flexural strength, strain energy, and ductility. Test data reveal that concrete reinforced with 4 percent steel fibers by weight possesses nearly twice the flexural strength of plain concrete (Hanna 1977). Other studies indicate that these fibers act as crack arresters; that is, the fibers restrict the growth of microcracks in concrete (Romualdi and Batson 1963).

Lunar Materials

To produce concrete in space, lunar rocks will make excellent aggregate. Concrete specimens made with terrestrial basalt similar to lunar basalt have been tested in our laboratories. As expected, basalt concretes have compressive strengths of 6000 psi (41.4 MN/m^2) and higher. Moon dust, a pozzolanic substance similar to fly ash (a byproduct of coal-fired power plants producing electricity), can be used to reduce cement requirements by as much as 15 percent without degrading concrete quality (McCrone and Delly 1973).

Once a lunar base is established for the extraction of lunar oxygen (Davis 1983), water produced in the oxygen extraction process can be used for making concrete. The hydrogen needed to extract the oxygen may itself be extractable from the lunar soil, where it has been implanted by the solar wind to a concentration of 100 ppm (Carter 1985). However, if hydrogen extraction proves to be economically infeasible, the hydrogen can be brought up from the Earth.

A study of mare basalt and highland anorthosite (NASA CP-2031) brought back by the Apollo 17 astronauts reveals that it is possible to manufacture on the Moon both glass fibers (Subramanian and Austin 1978) and a cement which is relatively high in aluminum oxide (Takashima and Amano 1960) by sintering lunar materials in a solar furnace. Concrete made from this type of cement is strong but crumbles when it absorbs moisture. On the dry Moon, such a cement offers the advantage without the disadvantage.

Because of the low gravity and the lack of an atmosphere on the Moon, the transport of construction materials from the lunar surface to Earth orbit can be accomplished with tremendous energy savings in comparison to shipping them from the Earth's surface (Chapman 1984).

Mixing and Casting

Concrete would be mixed and cast in a Space Shuttle external tank that provides temperature, pressure, and humidity controls. Figure 38 shows a conceptual space concrete plant. Two rockets at the ends of a tube protruding from the module spin the system to provide the desired centrifugal force (0.5 *g*). Centrifugal force makes conventional mixers usable in a weightless environment.

Concrete materials would be pumped from storage bins through tubes to the mixers. From the intake position, the mixers turn 90° to an upright position and then rotate around their own axes to agitate the mixture. By rotating another 90° so that the feed openings face outward, the mixers allow the fresh concrete to be discharged into receiving buckets, from which spiral mass drivers can pump the wet concrete to the casting location.

After discharging into forms, the concrete would be consolidated, using appropriate vibrators, and finished with large trowels by human operators, working in the shirt-sleeve environment. In terrestrial construction, forms are generally removed 7 days after casting. However, a low-gravity environment will put less stress on the curing concrete, and therefore it will be possible to shorten the 7-day requirement to 1 day by decreasing the spin rate of the system. Since water will be expensive to manufacture in space, condensers can be utilized to capture the moisture evaporated during the curing period. As soon as the concrete has dried sufficiently, the structure is ready to be moved out of the module. The application of slip-forming techniques will make it possible to build a continuous cylindrical space station of any size.

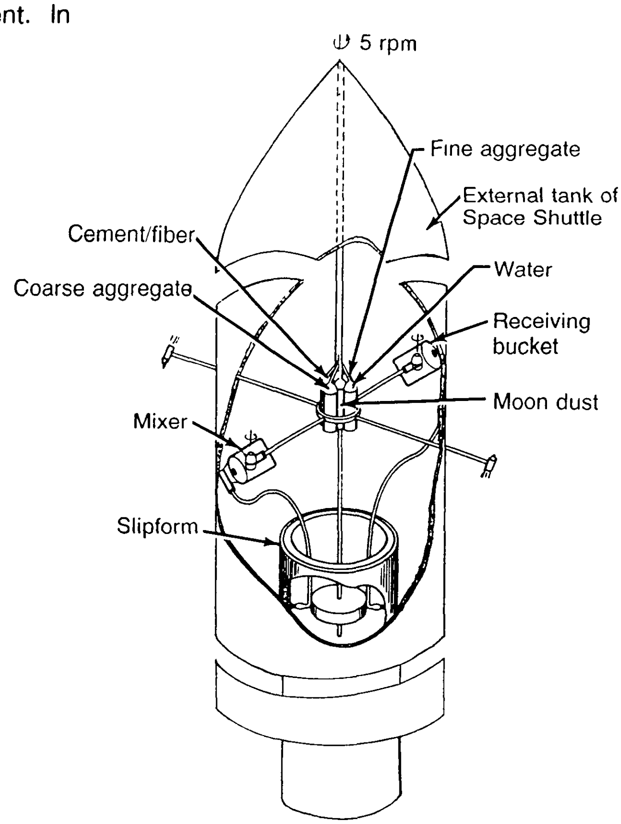

Figure 38

Conceptual Concrete Plant in Space

Advantages

A concrete space station has the following advantages.

1. *Large mass:* An orbiting station is charged with kinetic energy, of which the velocity is a relative factor and the mass an absolute factor. In the event of a collision, a larger mass that possesses greater momentum will always have the dynamic advantage over a smaller one. Reinforced concrete structures have this advantage over less massive structures.

2. *Compartmentalization:* One of the strong features of concrete is that it can be cast at room temperature into any monolithic configuration. A concrete space structure should be compartmentalized to prevent total destruction in case the station is hit by something or a fire occurs.

3. *Concrete strength:* In near-Earth space, temperature may vary from -200°F (-130°C) in the dark to +200°F (+93°C) facing the Sun (Heppenheimer 1977). The effect of temperature on material strength is an important consideration in structural design. Some materials soften when heated, and others become brittle when cooled. Figure 39 shows that the strength of concrete heated to 200°F (93°C) is practically unaffected (Abrams 1973). And the strength of concrete *increases* as the temperature goes below the freezing point. Figure 40 shows the strength-temperature relationship for normal weight maintained at 75-percent relative humidity. Surprisingly, the strength at 150°F (100°C) is 2-1/2 times the strength at room temperature and at 250°F (160°C) is 2 times that at room temperature (Monfore and Lentz 1962). [The strength of concrete in an oven-dry condition remains constant in the temperature range from -250°F (-160°C) to +250°F (+120°C).]

4. *Heat resistance:* Whereas aluminum softens at 600°F (320°C), concrete is thermally stable up to 1100°F (600°C) (Harmathy 1979). Its low thermal conductivity and high specific heat make it an excellent heat-resistant construction material.

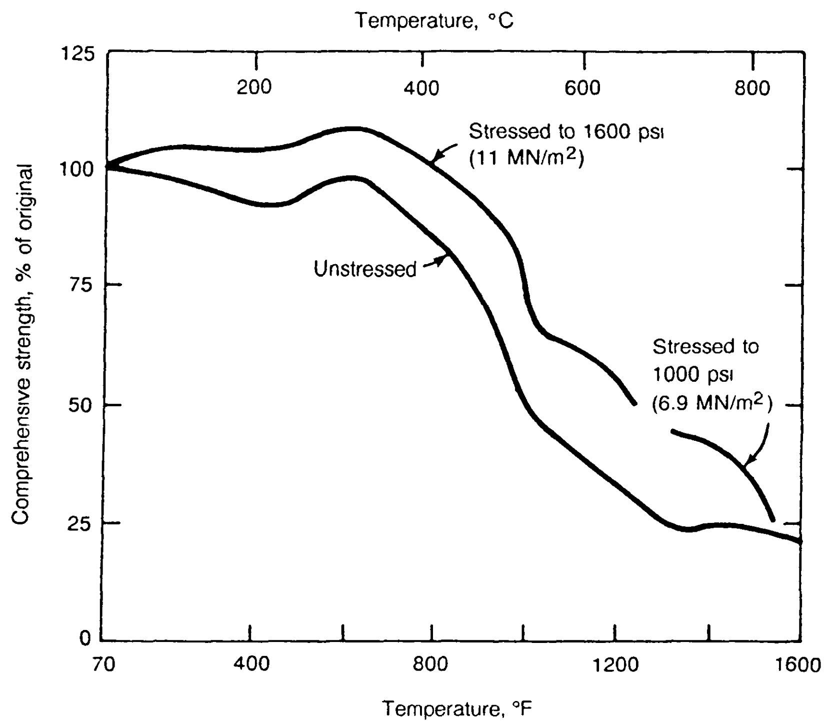

Figure 39

Effect of Temperature on Compressive Strength of Siliceous Aggregate Concrete

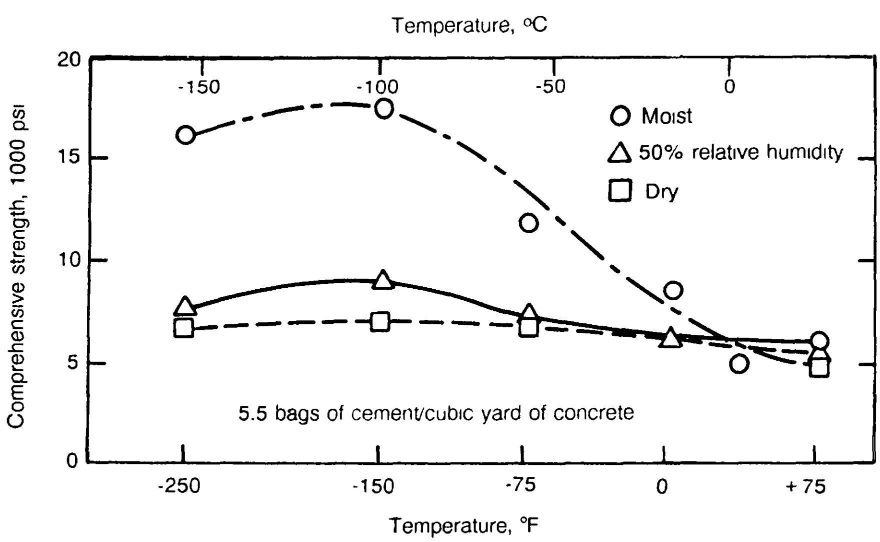

Figure 40

Effect of Low Temperatures on Strength of Moist Concrete

5. *Radiation shielding:* Most radiation energy will be converted into heat energy in the course of attenuation in an exposed body. A simple fact explains why concrete is good for radiation shielding. In general, a hardened concrete consists of 95 percent aggregate and cement and 5 percent water by weight. In the energy released from a fission explosion 97 percent is from gamma rays and 3 percent from fast-flying neutrons. Both aggregate and cement—nonmetallic and inorganic—are excellent materials for absorbing gamma-ray energy, whereas water is the best substance for absorbing neutron energy. Although the percentages for concrete composition are not exactly equal to those for fission energy, they are close to proportional. Because of its radiation-shielding property, concrete is used in the construction of nuclear power plants. Thus concrete would provide a large margin of safety against the hazard of naturally occurring radiation on the Moon.

6. *Abrasion resistance:* In addition to asteroids and meteorites, there are micrometeorites and cosmic dust traveling in space with a relative speed of 25 miles/sec (40 km/sec) (Heide 1964). These microparticles may abrade the surface of the space station because of the enormous differential velocities. Concrete possesses high abrasion resistance, resistance which increases proportionally with concrete strength. The relative depth of a crater made by a microparticle is less in a thick concrete wall than in a thinner wall made of another material.

7. *Effect of vacuum:* In a vacuum, the free moisture in concrete may eventually evaporate, but not the chemically bonded water. Figure 39 shows that the loss of free moisture, which generally takes place around 212°F (100°C), has no adverse effect on concrete strength.

A shortcoming that a pressurized concrete structure may have relates to the airtightness of concrete. To overcome this difficulty, an epoxy coating or other sealant can be applied on the internal surface of the concrete structure.

Conclusion

Reinforced concrete has many material and structural merits for the proposed space station. Its cost-effectiveness depends on the availability of lunar materials. With such materials, only 1 percent or less of the mass of a concrete space structure would have to be transported from Earth.

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Lunar Cement

William N. Agosto

With the exception of water, the major constituents of terrestrial cements are present at all nine lunar sites from which samples have been returned.

Two examples of the most commonly used cement formulations (Mindess and Young 1981) are listed below.

Typical Portland Cement

Major constituents	% by wt.
CaO	63
SiO_2	22
Al_2O_3	6
Fe_2O_3	2.5
MgO	2.6
SO_3	2.0
K_2O	0.6
Na_2O	0.3
	99

High Alumina Cement

Major constituents	% by wt.
Al_2O_3	50
CaO	39
SiO_2	6
Fe_2O_3	1
MgO	1
SO_3	1
	98

All the above oxide constituents are found in lunar soils, basalts, and anorthosites except that iron oxide is in the ferrous form (FeO) and sulfur occurs as FeS in basalts and in sparsely scattered particles of meteoritic metal in the soil. However, with the exception of relatively rare cristobalite (SiO_2), these oxides are not present as individual phases but are combined in silicates and in mixed oxides [e.g., ilmenite ($FeTiO_3$)].

Lime (CaO) is most abundant on the Moon in the plagioclase ($CaAl_2Si_2O_8$) of highland anorthosites. The anorthosites are approximately 90 percent anorthite containing 20 percent lime by weight (McKay and Williams 1979).

It may be possible to enrich the lime content of anorthite to levels like those in Portland cement by pyrolyzing it with lunar-derived phosphate in a reaction like

$$\underbrace{Ca_3(PO_4)_2}_{\text{whitlockite}} + \underbrace{CaO \bullet Al_2O_3 \bullet 2SiO_2}_{\text{anorthite}} \xrightarrow{\text{vacuum solar furnace}} \underbrace{4CaO \bullet Al_2O_3 \bullet 2SiO_2}_{\text{slag}} + 2P + 2.5\,O_2 \quad (1)$$

If workable, reaction (1) increases lime content from 20 percent by weight in anorthite to 50 percent by weight in the slag. A similar reaction has been proposed by Ellis M. Gartner of Construction Technology Laboratories, the research group of the Portland Cement Association. That reaction includes carbon as a reductant and uses apatite as the lunar phosphate. However, reductants may not be required in the high vacuum of the lunar environment. Both phosphate reactions need to be thermodynamically tested at the bench level.

Phosphate consumed in reaction (1) can be regenerated by reacting the phosphorus product with lunar augite pyroxenes at elevated temperatures in a reaction like

$$\underset{\text{augite}}{11(Ca_{.273}Mg_{.273}Fe_{.45})SiO_3} + 2P \longrightarrow \underset{\text{whitlockite}}{Ca_3(PO_4)_2} + 5Fe + \underset{\text{silica}}{8SiO_2} + \underset{\text{enstatite}}{3MgSiO_3} \qquad (2)$$

Colleagues and I (1980) have suggested that reaction (2) may be the process generating phosphate in certain stony-iron meteorites (the mesosiderites). In the meteorites, phosphorus is derived from meteoritic metal, where it occurs as a phosphide in an intermetallic phase. The same phosphide phase is found in metallic particles of lunar soil, which are derived from meteorites. These can be magnetically beneficiated as a source of iron, nickel, phosphorus, and cobalt (Agosto 1981). The soil metal contains as much as 11.5 percent by weight phosphorus, with an average of about 1 percent phosphorus (Goldstein and Axon 1973). Lunar phosphate has also been found as a minor component of KREEP (potassium, rare earth elements, phosphorus) soils and basalts, notably Apollo 14, at a maximum of about 1 percent by weight.

Thus, the lunar soil could provide both the phosphate needed for reaction (1) and the reduced phosphorus needed for reaction (2). Alternatively, terrestrial phosphate could be transported to space as a reagent, with phosphorus losses in recycling replenished from lunar sources.

The oxide components for Portland cement may also be produced from the silicate minerals in the abundant lunar mare pyroxenes [like the augite used in reaction (2)] by the vacuum solar pyrolysis used in reaction (1) but without the need for a phosphate reagent (Agosto and King 1983). Sufficient sulfur for the formulation of cement might also be derived from the FeS in soil metal.

It may also be possible to obtain high alumina lunar cement directly by solar pyrolysis of anorthite derived from highland anorthosites. The oxide components of anorthite are alumina (Al_2O_3), lime (CaO), and silica (SiO_2). In a solar furnace, the silica would vaporize preferentially, leaving a residue enriched in lime and alumina within the composition range of high alumina cements (Agosto and Gadalla 1985).

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PART 3—Manufacturing and Fabrication

Sankar Sastri, Michael B. Duke, and Larry A. Haskin

Introduction

The ability to use nonterrestrial materials and energy and to utilize the special properties of space environments will allow the space enterprise to grow at an increased rate. We can envision a self-sufficient space economy, with centers of resource extraction and manufacturing off Earth that provide sustenance to colonies of people. However, in the next 25 years, the infrastructure for using space resources will concentrate on more limited goals, those that will have high leverage on the space economy.

Four general goals for use of nonterrestrial resources are

1. To decrease the cost of transporting various systems beyond low Earth orbit (LEO) by providing propellant or reaction mass at a reduced cost

2. To reduce or eliminate the transportation costs for systems emplaced on other planetary surfaces and in space by using indigenous materials

3. To increase supplies of energy to Earth orbit and the Earth

4. To provide previously unattainable products by utilizing the special materials and unique processing capabilities afforded by space environments

Several possibilities exist to make major augmentations to our space capability by providing access to materials in space:

1. Provision of liquid oxygen can significantly reduce the need to transport propellant from Earth to low Earth orbit and reduce the cost of transportation to and from a lunar base.

2. Provision of material can decrease the costs of insulation and of shielding against radiation and impact for satellites in Earth orbit and human habitats beyond low Earth orbit.

3. Structural material, including pressurizable volumes, could be provided for Earth orbit or lunar bases.

4. Byproducts from nonterrestrial processing systems could begin to make living in space easier.

5. Energy collected in space could be used directly or by conversion to electricity to carry out space manufacturing enterprises.

6. Space debris could be recovered and reused or put to a new use.

This report is deliberately conservative. Previous studies (Criswell 1980) have demonstrated that nearly anything one wants to make in space can be made from the raw materials available on the Moon or on near-Earth asteroids. We have looked instead at what is most easily accomplished in the next 25 years.

The accessibility of material and energy off the Earth and the leverage that these nonterrestrial resources can exert on the space transportation system are important influences on the long-term goal of exploring the solar system. The next 25 years will provide the learning experience necessary to advance that activity more rapidly. The concept of "bootstrapping"—using the production capability to manufacture additional production equipment and expand production more rapidly than if all the production equipment had to be transported from Earth—can be tested and the ability to sustain human settlement beyond Earth can be demonstrated.

Research on separation of lunar materials and manufacture of useful products from them is in its infancy. Many avenues are left to be investigated. A few possible processes and products are described below.

Products

The least complicated technologies will not necessarily be the most cost-effective ones to manufacture products from nonterrestrial materials. It is nevertheless appealing to imagine that early space manufacture can be done by simple means. It seems that simplicity ought to correlate with economy or at least with probability of early application. Thus, we have chosen to explore the oxygen, metal, and silicate products that might be obtained from simple treatment of well-characterized materials from near-Earth space.

The ground rules of the exercise are these:

1. Starting materials are those substances found in greatest abundance at the lunar sites visited by the Apollo astronauts. More exotic lunar ores and water at the poles are excluded from consideration. So are all asteroidal materials, their exact nature being still unknown.

2. Raw materials for manufacture are materials in "as found" condition or materials upgraded or separated by only the simplest means.

3. Products are for use on the Moon or in orbit, not on Earth.

4. The additives, catalysts, and processing materials that must be supplied from Earth will be kept to a minimum.

5. Oxygen, perhaps extracted from ilmenite-rich material, will be an important early lunar product.

6. Materials used in space applications will be those available and adequate, not necessarily those traditionally envisioned or preferred.

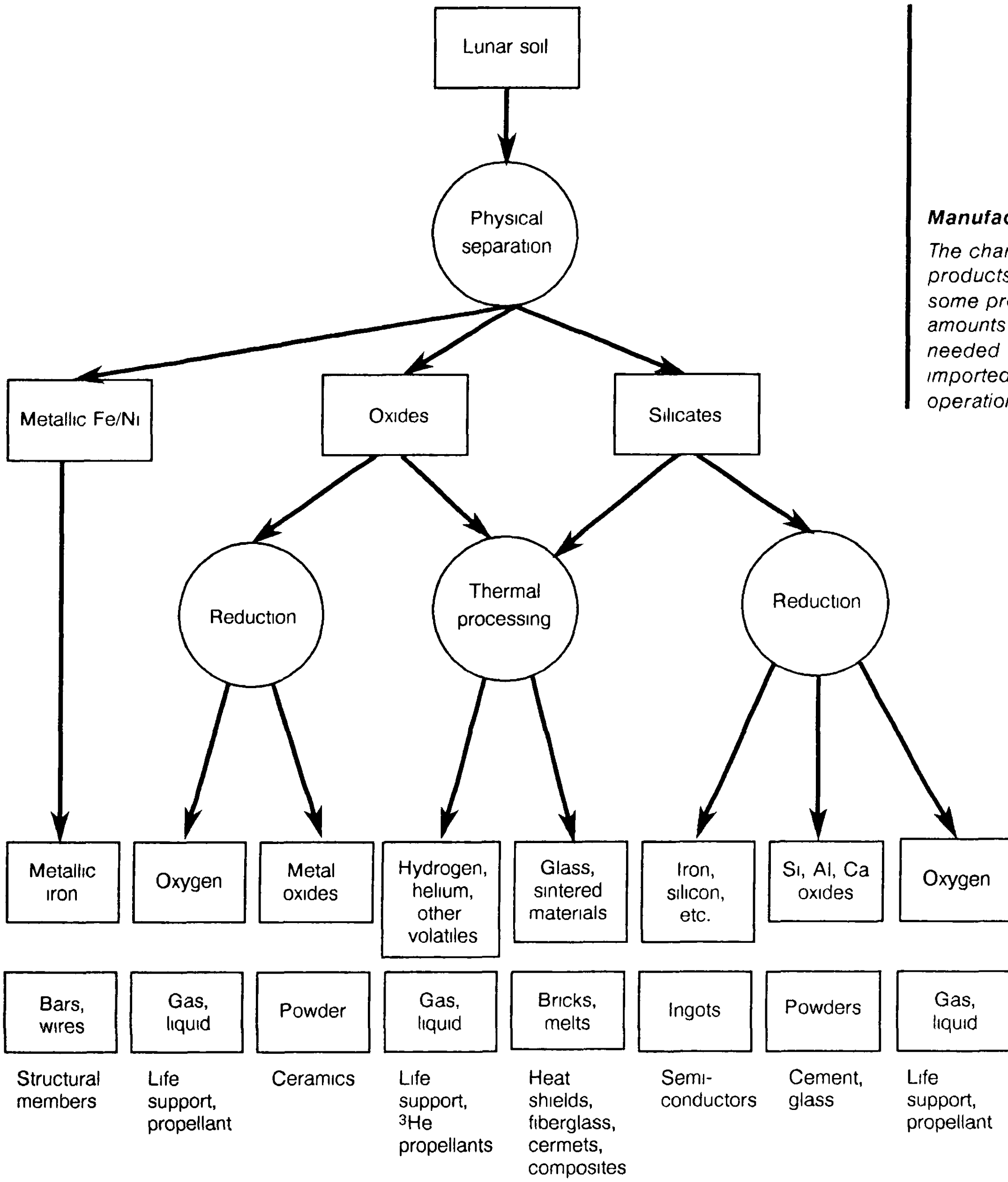
7. The quality of material used may not match that of similar material produced on Earth, and sizes and quantities will be adjusted accordingly.

8. The complex components that are necessary will be imported from Earth.

9. Steps in manufacture must be few, easy, and reliable.

10. Assembly and application of products must be simple and rapid and tolerances relatively loose.

11. All processes up through assembly should be reasonably automated but tended. Equipment should be easy for its operators to repair, optimize to actual conditions, and adapt to new feedstocks and applications.



Manufacturing on the Moon

The chart shows various sources and products utilizing lunar materials. For some products with special uses, small amounts of material from Earth may be needed. Conservation and recycling of imported materials will be important in operational systems, such as life support.

The scenario that could result from application of these ground rules to common materials at Apollo sites is limited but far from stifling. To make the problem tractable for this exercise, we have chosen to constrain our list of materials and products even more narrowly than the rules specify. Nevertheless, the examples we treat should be sufficient to illustrate the possibilities and the limitations.

The following are designated as starting materials:

I. Unprocessed lunar regolith

  A. Bulk soil
    1. Mare-derived; high-iron, high-silicon, low-aluminum, low-calcium
    2. Highland-derived; low-iron, high-silicon, high-aluminum, low-calcium
    3. Mixed origin; intermediate-composition

  B. Rocks
    1. Mare basalt [$CaAl_2Si_2O_8$ (plagioclase) and $(Mg,Fe)SiO_3$ (low-calcium pyroxene)]
    2. Highland igneous rocks
      a. Anorthite (primarily plagioclase)
      b. Dunite [primarily $(Mg,Fe)_2SiO_4$ (olivine)]
      c. Troctolite (mixtures of plagioclase and olivine)
      d. Norite (mixtures of plagioclase and low-calcium pyroxene)
    3. Breccias (physical mixtures of rock, mineral, and glass fragments)

II. Minimally processed regolith (no chemical extraction)

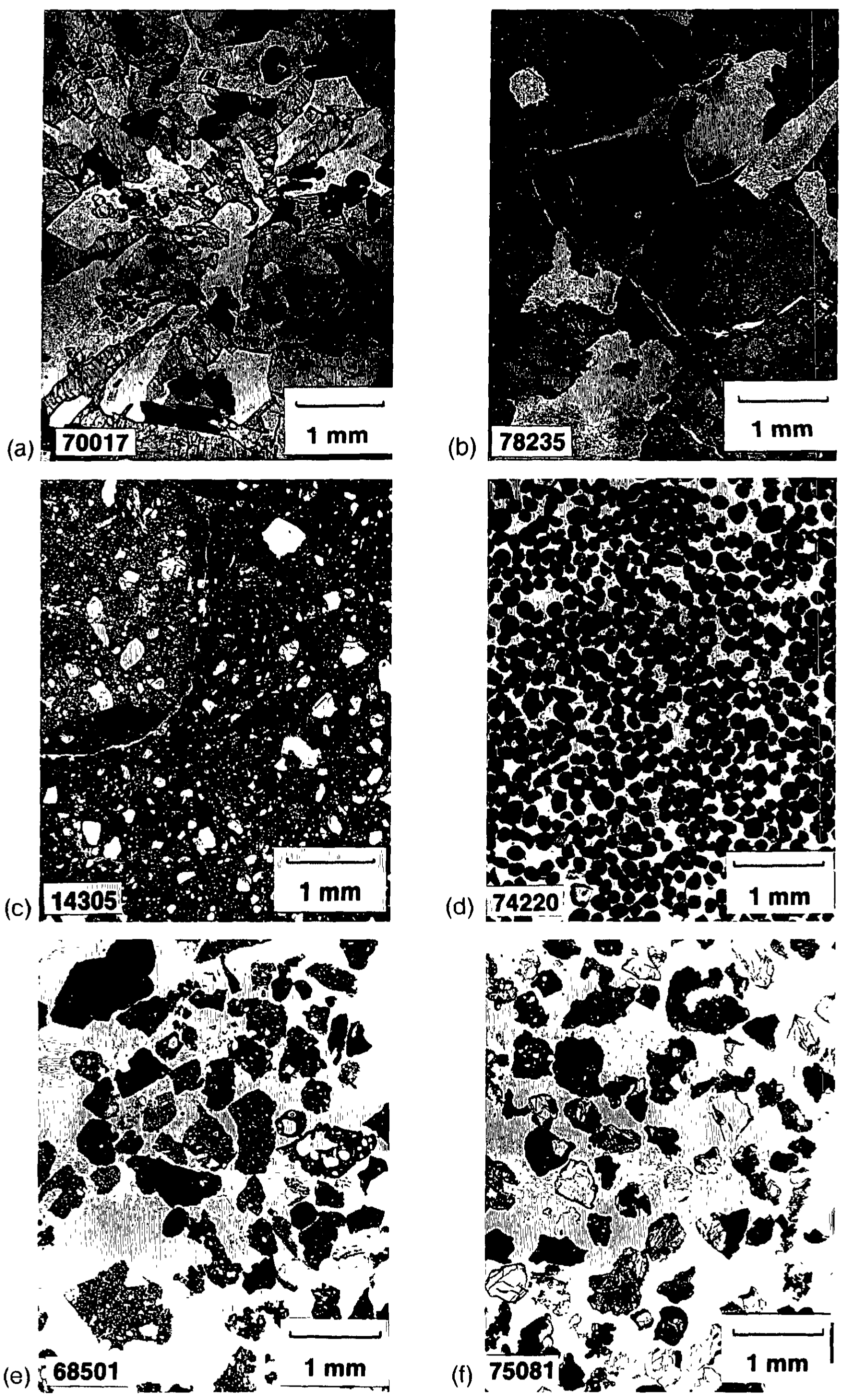
  A. Magnetic iron-nickel alloys plus iron-bearing glassy "agglutinates" (separated magnetically)

  B. Ilmenite concentrate, $FeTiO_3$ (separated electrostatically)

  C. Plagioclase concentrate (separated paramagnetically or electrostatically)

  D. Residues from separations of A through C

  E. Volatiles (H_2, N_2, He) driven off thermally



Intermediate Products

Lunar rocks and the regolith consist of minerals and glasses, which can be separated by several means. Here, a variety of lunar materials are shown as they appear in very thin slices viewed with a microscope in transmitted light.

a. Basalt, consisting of intergrown crystals of plagioclase feldspar (clear), olivine and pyroxene (dark, transparent), and ilmenite (black, opaque).

b. Norite, consisting primarily of plagioclase feldspar and low-calcium pyroxene, in coarse grains.

c. Breccia, showing very fine-grained material enclosing larger rock fragments

d. Orange soil. This is a peculiar soil consisting primarily of beads of orange glass of basaltic composition, probably formed in a volcanic fire fountain.

e. Fragments from typical highland regolith. Agglutinates are fused regolith material, which formed tiny gas bubbles as they melted and were quenched.

f Typical millimeter-size fragments in mare regolith. At millimeter sizes, most lunar regolith grains are complex, consisting of more than one mineral. At smaller sizes, a higher fraction of the grains consist of only a single mineral.

Mineral separation (beneficiation) techniques utilize the different properties of the minerals and glasses to separate them. The techniques include size, magnetic, specific gravity, and electrostatic separation. Mixed grains are more difficult to separate by physical means.

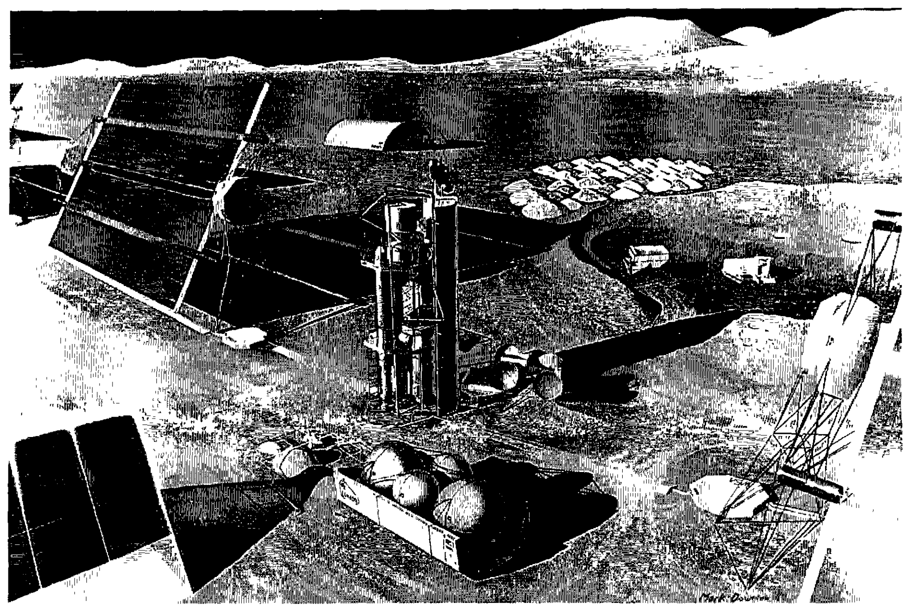
Chemical Processes

a. Ilmenite Reduction

A facility such as this could use hydrogen to chemically reduce ilmenite ($FeTiO_3$), thus producing iron metal, titanium dioxide, and water. The water is then electrolyzed, to split the hydrogen and oxygen. The hydrogen is recycled to the reduction process, and the oxygen is liquefied and stored for use. The oxygen has use in the transportation system as propellant, in life support systems, and in other chemical processing, thereby offsetting the need to import it from Earth.

The residue from the process may have uses as well. It typically would consist of an intimate mixture of iron (alloyed with small amounts of silicon and titanium) and titanium dioxide (rutile). The metal can be separated either by melting or by a chemical process (e.g., carbonyl processing). The titanium dioxide may find use as a ceramic material. The combined slag from the process may find use as a structural material through allowing it to sinter (compact and harden) while it cools from high temperature.

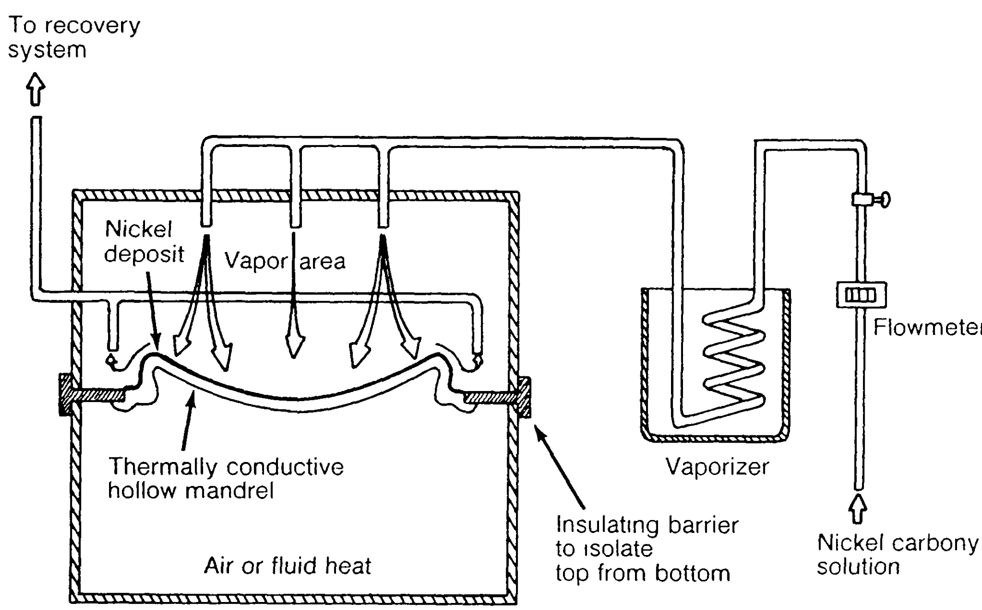
Artist: Mark Dowman

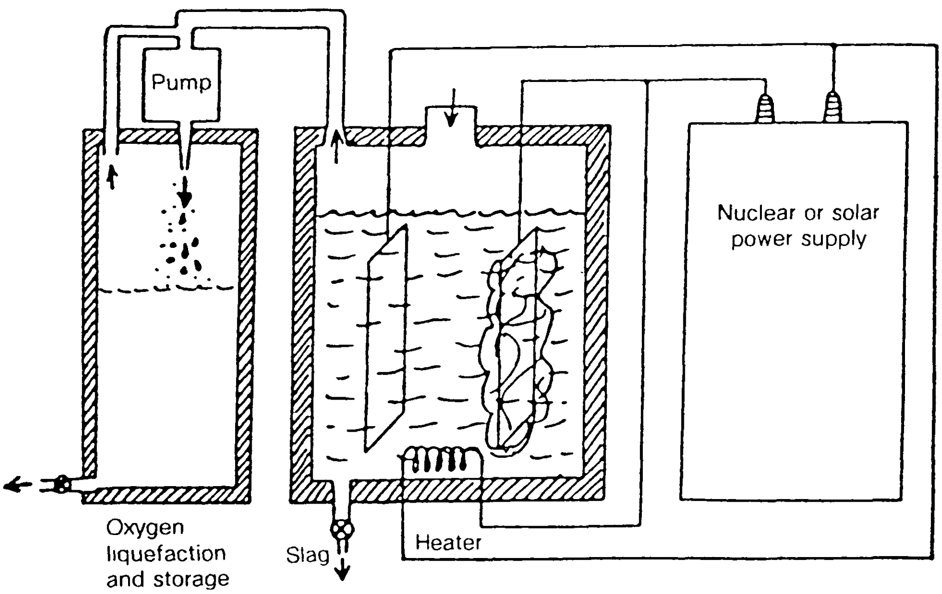


b. Carbonyl Processing

Carbonyl processing (the Mond process) is a well-known procedure for extracting nickel from metal by reaction with carbon monoxide gas. The metals in the residue from the hydrogen reduction of ilmenite could be separated from one another and from the rutile by the carbonyl process. Or the process could be applied to meteorites found in the lunar regolith to separate the nickel and iron in them. In addition, as depicted in the illustration, the gaseous carbonyl can be used to directly deposit metal coatings or even metal objects.

Courtesy of Vaporform Products; taken from Meinel 1985, p. 157.



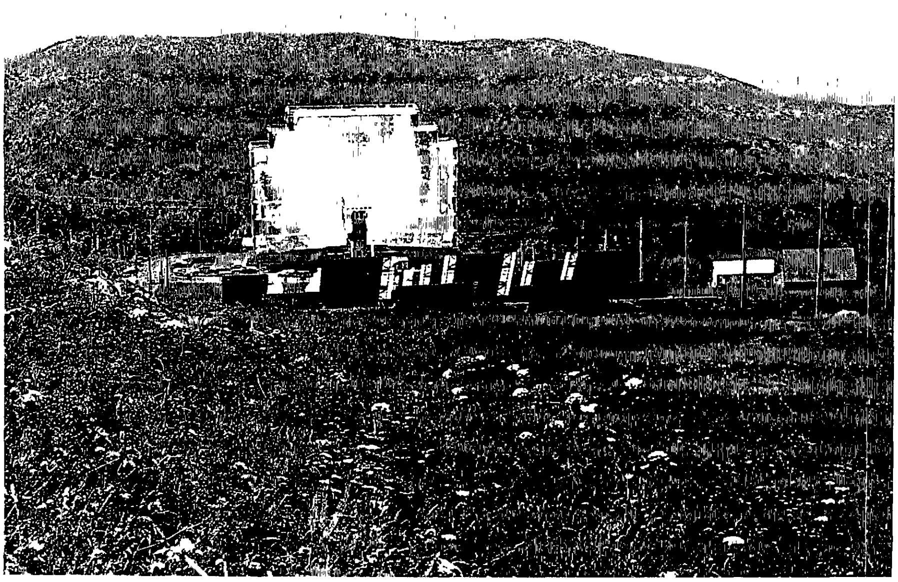


Magma electrolysis cell

c. Electrolysis

Silicate electrolysis is similar in concept to the simple electrolysis cell used to dissociate water into hydrogen and oxygen. Instead of water, molten silicate forms the solution which conducts electrons from the cathode to the anode. As those electrons are transferred, the iron in the silicate is reduced to metal and oxygen is released. Recent studies (Lindstrom and Haskin 1979) have shown that some titanium and silicon can also be reduced to metal in this manner. The electrodes are the critical element of the electrolysis cell If they become corroded or damaged, the cell will cease to function If the rate of deterioration is high and new electrodes need to be brought from Earth regularly, part of the benefit of using the indigenous materials is lost.

From Lewis, Jones, and Farrand 1988, p. 116.



d. Solar Furnace

It is possible to separate some elements from molten materials simply on the basis of their volatility. Solar concentrators, such as this one in Odeillo, France, can achieve temperatures higher than 3500°C. If typical lunar rocks are heated to the vicinity of 2000°C. first sodium and potassium evaporate, then silicon and iron, leaving primarily a mixture of calcium, aluminum, magnesium, and titanium. Some reduction to metal may occur. The resulting residue may be quite similar to compounds used in Portland cements on Earth.

Photo: Elbert A. King

III. Maximally processed regolith (chemical extraction)

A. Elemental oxygen (product of reduction of lunar material)

B. Residues from oxygen smelting (e.g., from the ilmenite reduction process): rutile (TiO_2), elemental iron, silicate impurities, all intimately mixed

C. Products from carbonyl processing of metal concentrates
   1. High purity iron metal
   2. High purity nickel metal
   3. Rutile plus silicate impurities

D. Products of electrolysis of basalt
   1. Iron metal, with perhaps up to 2 percent manganese and chromium
   2. Iron metal with several percent titanium
   3. Iron metal with several percent silicon

E. Products from solar furnace evaporation of silicates
   1. Calcium aluminate cement
   2. Metals, including iron and silicon

Indigenous conditions assumed are vacuum, sunlight, low gravity on the Moon, and microgravity in near-Earth space. Tools and facilities that should be available include solar furnaces and electrical power at megawatt levels.

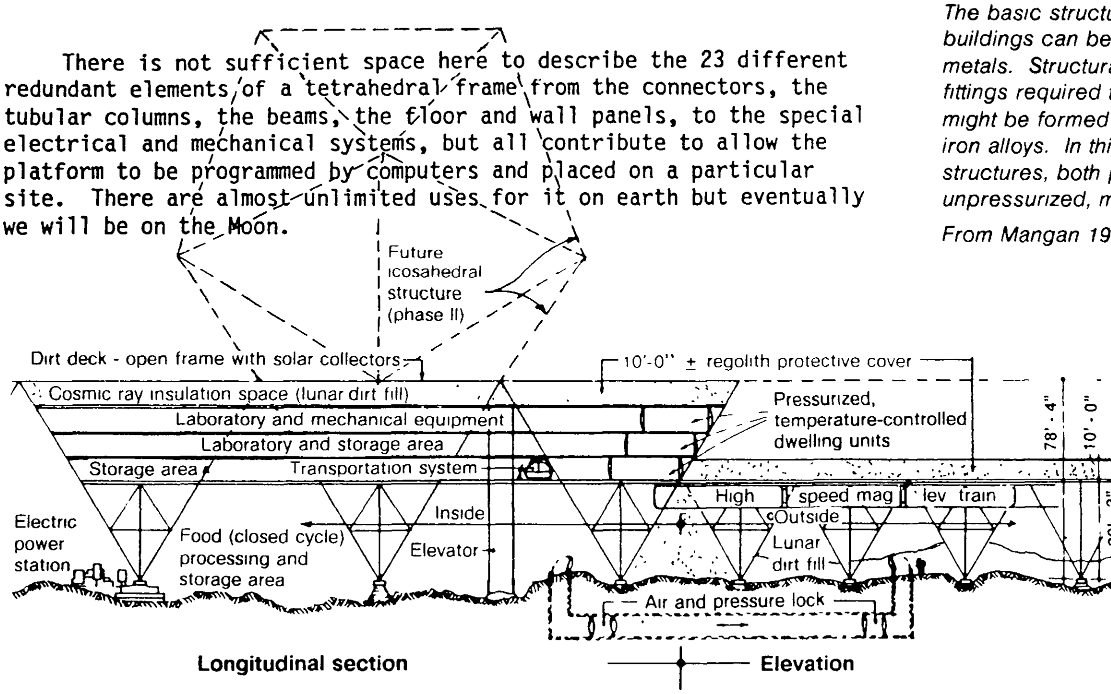
From this set of starting materials and facilities, the following classes of products are possible. These are evaluated with respect to properties attainable without further change or purification. Additional equipment needed to produce the products from the starting materials is identified. Also, additives that in small quantities could greatly improve the caliber of these products are identified. Gases, such as oxygen, hydrogen, carbon dioxide, and helium, are useful as generated and do not require further processing.

I. Metal-based

   A. Extruded products—beams, rods, wires

   B. Cast products—beams, rods, containers

   C. Rolled parts—plates, foils, beams



The Expandable Platform on the Moon

Structural Framework

The basic structural framework for buildings can be produced from lunar metals. Structural members and the fittings required to join them together might be formed by extruding lunar iron or iron alloys. In this manner, extensive structures, both pressurized and unpressurized, might be built.

From Mangan 1988, p. 380.

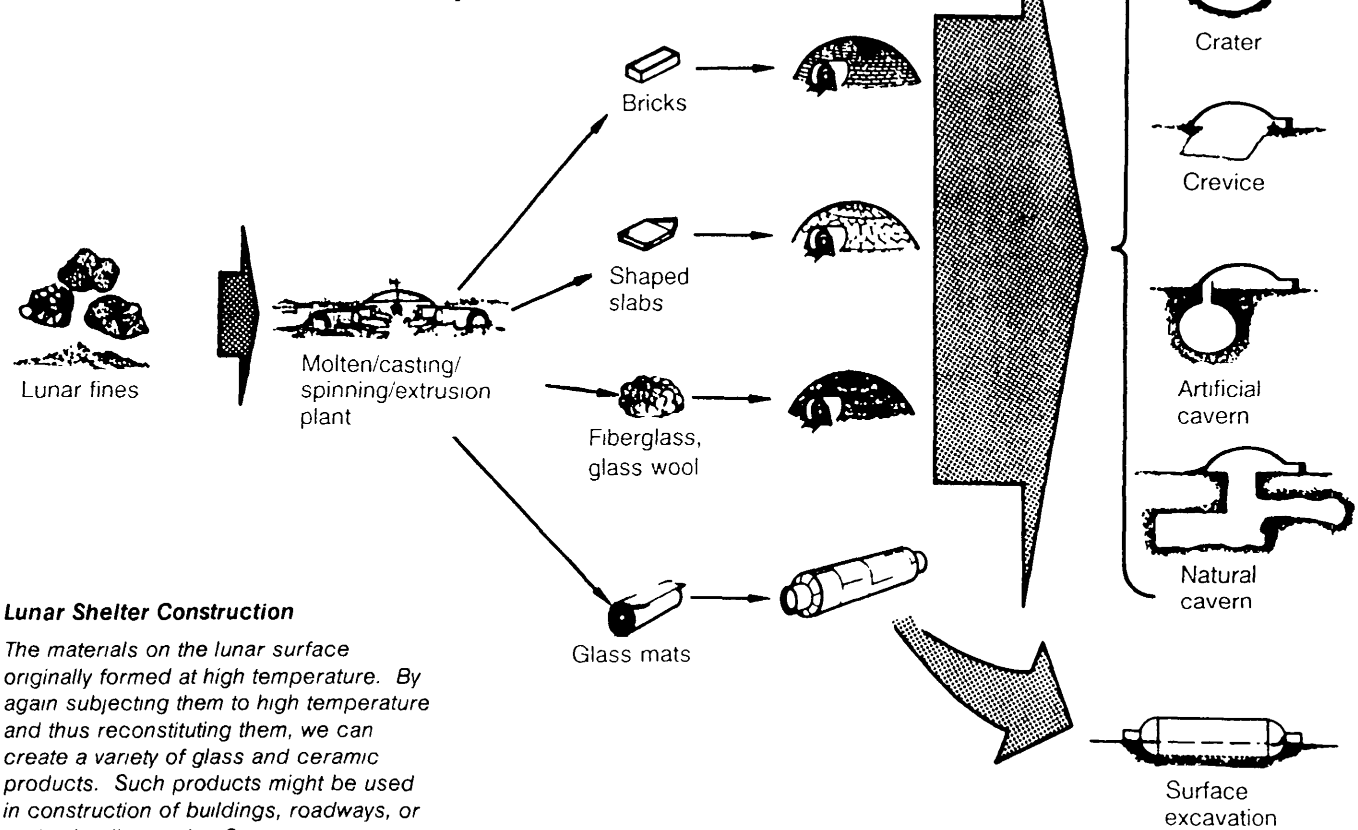
II. Silicate-based

A. Glasses—fibers, rods, light pipes, beams, bricks, coatings, sheets

B. Ceramics, cermets*—containers, bricks, pipes

C. Composites—cement, concrete

D. Sintered silicates—bricks, plates



Lunar Shelter Construction

The materials on the lunar surface originally formed at high temperature. By again subjecting them to high temperature and thus reconstituting them, we can create a variety of glass and ceramic products. Such products might be used in construction of buildings, roadways, or rocket landing pads. Construction materials derived from lunar regolith could be used in combination with excavations of the subsurface to expand habitable volume.

*A *cermet* [*cer* amic + *met* al] is a strong alloy of a heat-resistant compound (as titanium carbide) and a metal (as nickel) used especially for turbine blades. Also called a *ceramal*.

Iron and Alloys of Iron

Sankar Sastri

All lunar soil contains iron in the metallic form, mostly as an iron-nickel alloy in concentrations of a few tenths of 1 percent (Nozette 1983). See figure 1. Some of this free iron can easily be separated by magnetic means (Shedlovsky et al. 1970; Goldstein, Axon, and Yen 1972). It is estimated that the magnetic separation of 100 000 tons of lunar soil would yield 150-200 tons of iron. Agglutinates (glass-bonded aggregates of soil fragments) contain metallic iron which could be extracted by melting and made into powder-metallurgy products (Romig and Goldstein 1976, Criswell 1981). However, agglutinate metal is so finely dispersed that it may be difficult or impossible to separate.

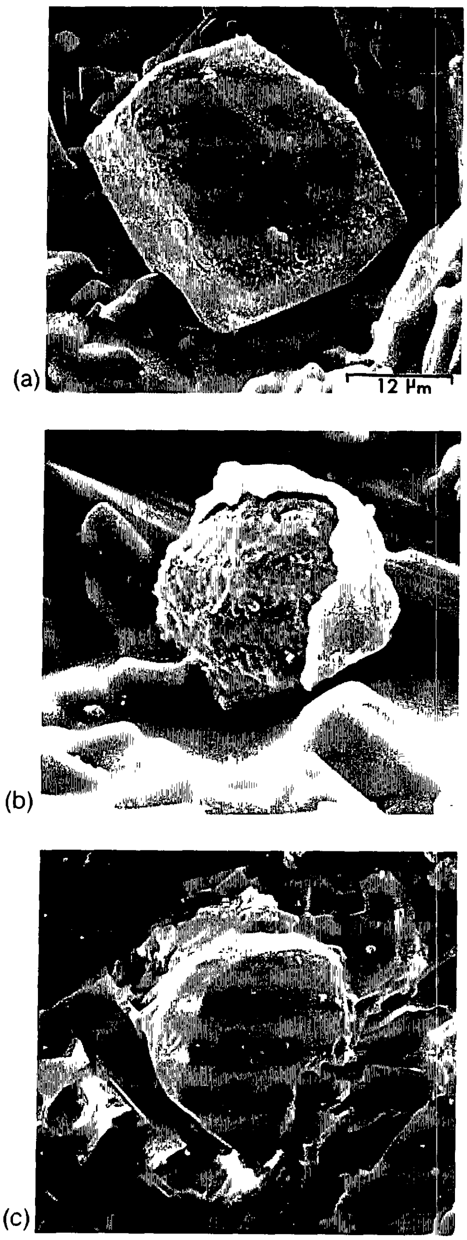


Figure 1

Iron in Lunar Soil

Many of the highly recrystallized breccias from Apollo 14 contain vugs with well-developed crystals that extend from the vug walls and bridge open spaces. Many of the larger vugs contain metallic crystals of iron or nickel-iron.

a. This photograph taken with a scanning electron microscope (SEM) shows a euhedral iron crystal. The tetrahexahedron has an axis of four-fold symmetry projecting toward the upper right of the photograph. The crystal contains no detectable nickel (less than 1 percent).

b. This SEM photograph shows a nickel-iron crystal that contains about 12 percent nickel. Because the tetrahexahedron was photographed along an axis of three-fold symmetry, it appears to be hexagonal. The crystal is partially covered with a coating of iron sulfide, presumably troilite. The rough texture of the nickel-iron crystal may have been caused by a former coating of troilite.

c. The crystal habit of such nickel-iron particles commonly is not obvious. Only at magnifications above 1000X can crystal face development be observed. The near spheroidal shape of this particle is typical of those photographed with the scanning electron microscope. This nickel-iron crystal contains about 4 percent nickel.

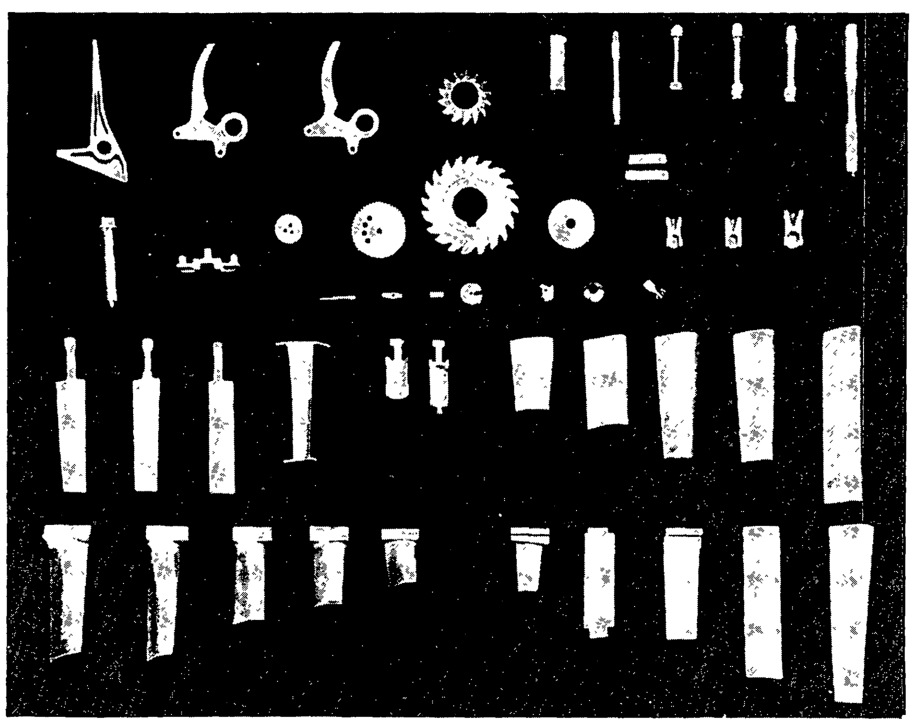
These crystals are thought to have been deposited from a hot vapor during the cooling of the large ejecta blanket from the impact that formed the Imbrian Basin on the Moon. Such a process is only one source of the metallic fragments in the lunar soil. Other iron-nickel fragments are pieces of meteorites that have crashed into the Moon.

Photographs and their interpretation taken from McKay et al. 1972, pp. 745-746

The basalts in the lunar maria contain up to 17 percent chemically combined iron, primarily in ilmenite, olivine, and pyroxene. And ilmenite ($FeTiO_3$) concentrations in lunar soil are of fairly high grade compared to deposits on Earth. A variety of extraction schemes have been proposed for recovering metallic iron from these silicates and oxides: electrolysis of molten lava (Lindstrom and Haskin 1979), a carbochlorination process (Rao et al. 1979), solar furnace evaporation (King 1982), a carbonyl process (Meinel 1985), a hydrofluoric acid leach process (Waldron 1985), and hydrogen reduction of ilmenite (Williams 1985). Even though considerable work is needed to evaluate and test these processes for feasibility in a lunar environment, the abundance of iron and its relative ease of separation suggest that metallic iron and its binary alloys may find wide application in large-scale space operations.

Characteristics and Potential Uses

Table 1 provides a list of the characteristics and potential uses of the pure iron and iron alloys which might be readily produced from lunar materials.



Casting Iron Parts

Iron parts are cast on Earth by pouring liquid metal into molds. Many intricate parts that would be difficult to machine can be made in this manner. The lunar equivalent could use iron or iron alloy produced as a byproduct of oxygen extraction and poured into "sand" molds made from lunar soil.

Courtesy of the Association of Iron and Steel Engineers, reprinted from The Making, Shaping and Treating of Steel, *10th ed., fig. 40-6*

TABLE 1. *Applications of Iron and Alloys of Iron*

Name	Composition	Characteristics	Uses
Ingot iron	Pure iron (industrial grade)	Ultimate tensile strength (UTS) 290-331 megapascals (MN/m^2) or 42-48 x 10^3 psi Elongation (el) 22-28%	Structures, beams, plates
Iron whiskers	Single-crystal pure iron fibers	0.00004-in. diameter UTS as high as 3448 MN/m^2 (500 x 10^3 psi)	Structures Electronics parts
Iron powder	Free of carbon and sulfur	10- to 40-micron powder	Propellants, Small powder-metallurgy parts—mechanical, electrical, and magnetic
Carbonyl iron powder		UTS 193-275 MN/m^2 (28-40 x 10^3 psi) el 30-40%	Propellants Powder-metallurgy parts Coatings for containers, walls
Iron-silicon alloy	Fe and Si form a solid solution up to 4.5% Si	UTS 345-414 MN/m^2 (50-60 x 10^3 psi) el 8-22%	Structures, beams, Motor transformer parts
Iron-nickel alloys	Fe and Ni form a continuous series of solid solutions	For 47-55% Ni, UTS 483-621 MN/m^2 (70-90 x 10^3 psi) and el 30-50% Ni increases UTS without loss of ductility	Structures Containers
Iron-titanium alloys	Fe and Ti form a eutectic solution	Ti increases hardness and strength	Structures Containers
Iron-manganese alloys	A range of Fe-Mn alloys are possible	For 1% Mn, UTS 414 MN/m^2 (60 x 10^3 psi) and el 40% Mn increases strength, hardness, and hardenability	Structures, beams
High-purity iron	Ultra-pure	Extremely difficult to produce on Earth High corrosion resistance Can produce high-strength, defect-free single-crystal or directionally solidified parts	Pressure vessels Solar mirrors Sheets Containers

The simple alloys described in table 1 may be relatively straightforward products of lunar metallurgy. Little is known, however, of the composition of the metal phase that forms directly from each of the processes described above. Process technology needs to be defined to establish the feasibility of providing the alloys.

Processes for Working Iron

A list of terrestrial manufacturing processes that might be used on iron and iron alloys in a nonterrestrial facility is shown in table 2. Criswell (1980) evaluated 200 manufacturing techniques and found more than 40 of them appropriate for a near-term, evolutionary space manufacturing facility. We consider all of the processes given in table 2 to be plausible for early application; however, when evaluated using the ground rules of our exercise, the processes that I discuss after the table appear to be the most feasible.

Casting

Casting, one of the oldest processes in the world, involves pouring liquid metal into a mold and allowing it to solidify in that shape (fig. 2). The casting process has to be modified for application in free space because gravity is so limited. Casting at a lunar facility in 1/6 gravity should be straightforward; however, mold construction techniques require study, particularly if indigenous materials are to be used for the molds.

TABLE 2. *Terrestrial Manufacturing Processes That Might Be Used on Lunar Iron*

Casting	Powder metallurgy	Hot working and cold working	Joining
Sand casting Shellmolding Die casting Investment casting Permanent molding Centrifugal casting	Compaction and sintering Hot isostatic pressing	Forging Rolling Extrusion Wire drawing Machining	Welding Brazing Soldering Fastening

Figure 2

Casting of Metal Ingots

Refined steel is poured from a refractory-lined ladle into molds of the desired size. The casting operation depicted is a continuous process, where large quantities of metal are being produced. A lunar operation would be on a much smaller scale and could produce castings that are directly usable, as well as the starting materials for rolled or extruded products. The ingot molds would be maintained at elevated temperature, waiting transfer to a rolling facility, in which they would be formed into bars or sheets.

Courtesy of the Association of Iron and Steel Engineers, reprinted from The Making, Shaping and Treating of Steel, *10th ed., fig. 20-2.*

Powder Metallurgy

Powder metallurgy consists of compacting fine metallic powder into a desired shape and sintering the shape (fig. 3). Lubricants may be required to separate pressed parts from the die. The absence of atmosphere in space prevents the formation of oxides or other contaminating layers on the powders and thus may promote the formation of high quality parts.

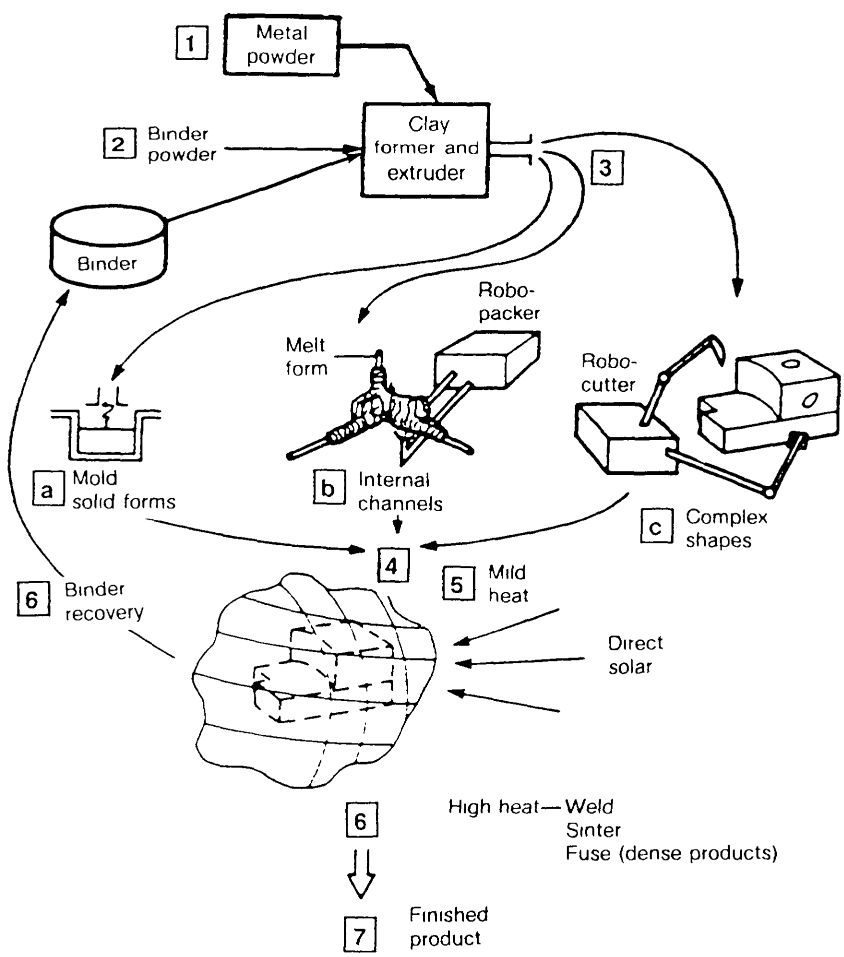


Figure 3

Powder Metallurgy

An alternative process for forming objects of metal is to compress and heat a metal powder in a mold. Iron powder derived from the metal in lunar soil or from byproducts of oxygen extraction may be molded in this manner for small manufactured items.

Here we see three ways in which the technique might be used. A metal powder [1] and a binder powder [2] are formed into a "clay" and extruded [3]. This clay is then used to create solid forms in a mold [4a], to shape intricate internal structures by molding metal powder around a meltable form [4b], or to make complex shapes [4c], which are then heated [5]. Similar techniques could be used for ceramics.

Taken from Criswell 1981, p. 397

Rolling

Rolling consists of passing a metal between two rolls which revolve in opposite directions, thereby decreasing the cross sectional area and increasing the length of the feedstock (fig. 4). Larger ingots are rolled into blooms having a cross section of more than 6 inches and finally into shapes such as plates, bars, rods, I-beams, and angles (fig. 5). Rolling should be readily adaptable to the space environment, as it does not depend on gravitational forces.

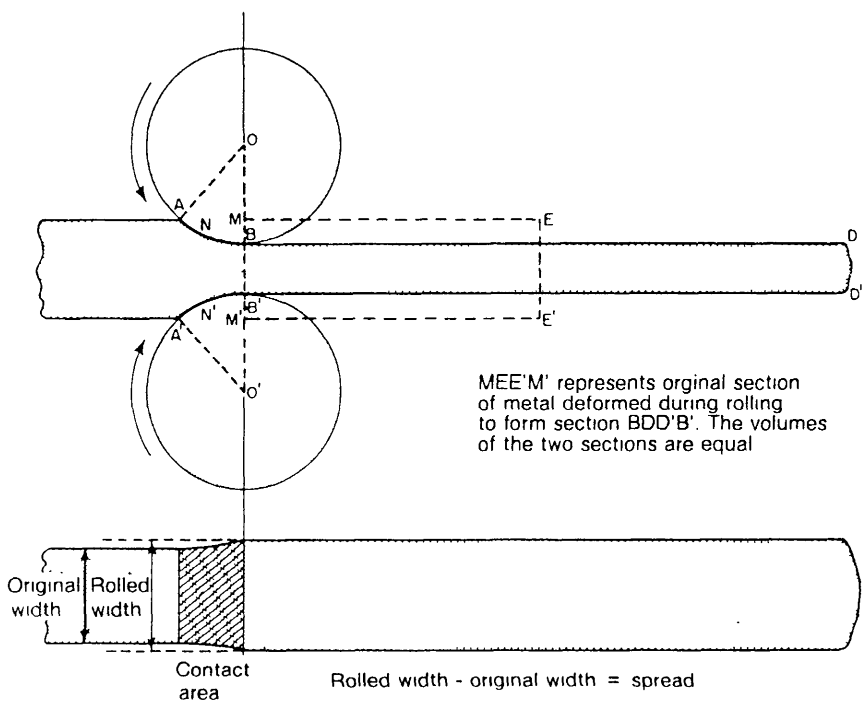


Figure 4

Rolling Steel

Hot steel in a plastic state can be rolled into a variety of products. Various types of rolling mills have been designed, depending on the type and properties of the desired product. Typically, an ingot of steel will pass through a series of rolls that gradually shape the steel. This diagram shows the basic principle.

Courtesy of the Association of Iron and Steel Engineers, reprinted from The Making, Shaping and Treating of Steel, *10th ed., fig. 22-9.*

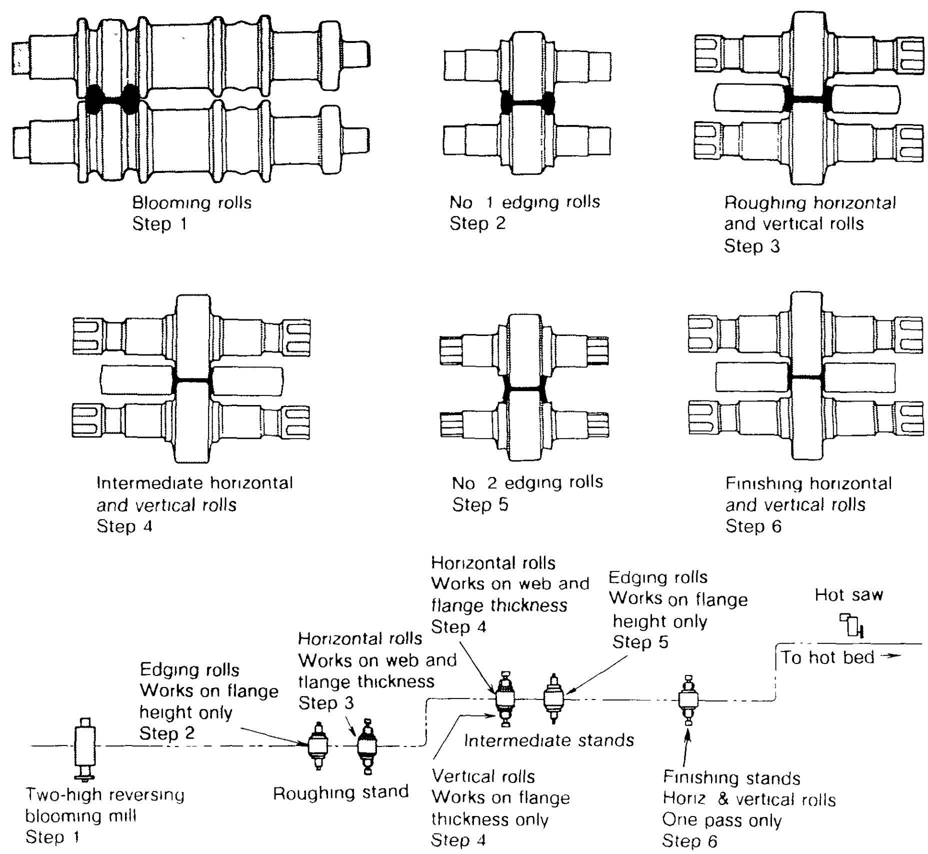


Figure 5

Shaping Bars

Rolling mills can produce a variety of shapes. Here, the rolled bar passes through several shaping steps on its way to becoming an H-bar.

Courtesy of the Association of Iron and Steel Engineers, reprinted from The Making, Shaping and Treating of Steel, *10th ed., fig. 23-3.*

Extrusion

Extrusion is essentially a hot working operation where a metal is extruded through a die or orifice that controls the cross sectional shape (fig. 6). Some common extruded shapes are rods, tubing, and window frames. Extrusion should be easily adapted to space operation.

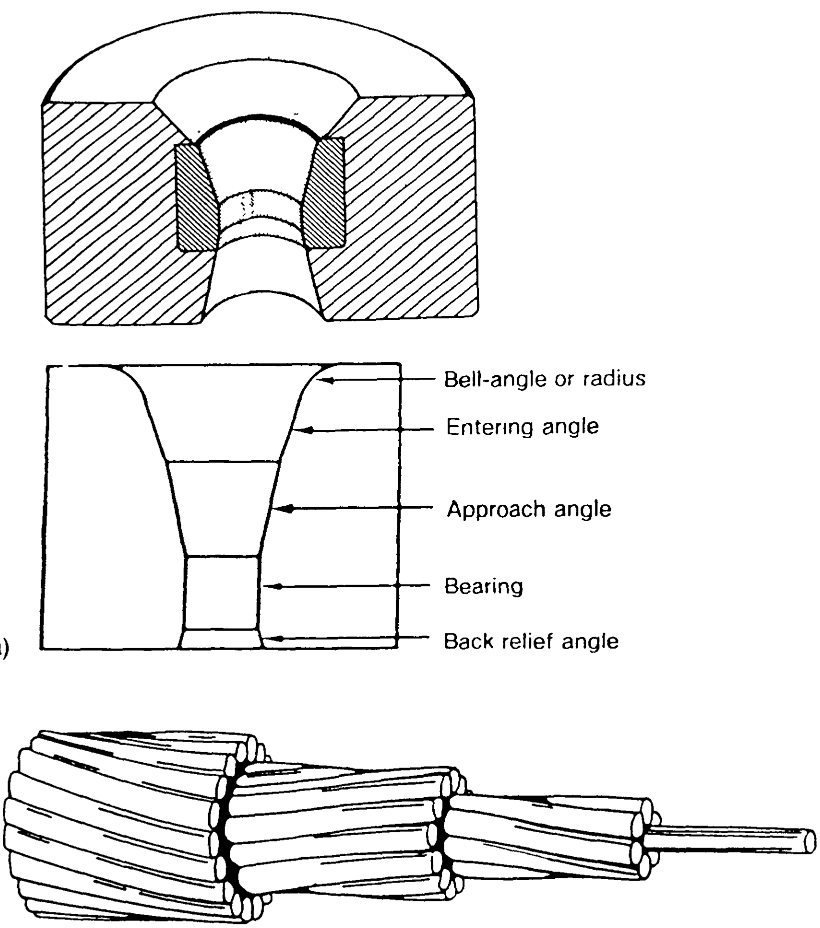


Figure 6

Wire

a. Die for Wire Pulling

b. Arrangement of Wires in a Cable

When bar stock has been produced, one of the further fabrication processes is the pulling of wire. In this process, a heated bar is pulled through a die, reducing its cross-sectional area by 10-45 percent. Several successively smaller dies may be necessary to produce wire of the appropriate diameter. Wires have a variety of uses. Two principal ones at a lunar base may be in cables used to prestress concrete structures and as supporting cables for structures.

Courtesy of the Association of Iron and Steel Engineers, reprinted from The Making, Shaping and Treating of Steel, *10th ed., figs. 31-13 & 31-14, and 9th ed., fig. 30-43.*

Cold Welding

Cold welding consists of joining two flat, clean surfaces of a metal by contact and application of pressure. Cold welding works by joining the surfaces at the molecular level. In space and on the Moon, where oxide layer formation is retarded (if not eliminated), cold welding has high potential. In particular, using ceramic rollers to cold roll ultra-pure metals may result in a low-cost way of cold welding. On the other hand, extreme care has to be exercised to keep the surfaces of high-purity metals separate so that undesired cold welding does not take place spontaneously.

Vapor Deposition

Vapor deposition involves allowing vapors of a metal to contact a surface in a closed chamber. On the surface metal layers build up atom by atom. The presence of vacuum makes this process a viable one in a space manufacturing facility. It is particularly suitable for applying thin coatings, such as making highly reflective mirrors.

Although these procedures are plausible for space manufacturing, all are in need of testing and demonstration to ensure that they can be used with typical nonterrestrial metals.

Glass and Ceramics

Larry A. Haskin

A variety of glasses and ceramics can be produced from bulk lunar materials or from separated components. Many glassy materials have been described in previous studies (Mackenzie and Claridge 1979, Criswell 1980). They include sintered (heated and pressed) regolith, quenched molten basalt, and transparent glass formed from fused plagioclase. No research has been carried out on lunar material or close simulants, so properties are not known in detail; however, common glass technologies such as molding and spinning seem feasible (fig. 7). Uses of glass include structural applications (bricks, slabs, beams, windows) and specialty applications (fiber strengtheners, insulation, heat shields, cables, light pipes). See figures 8 and 9.

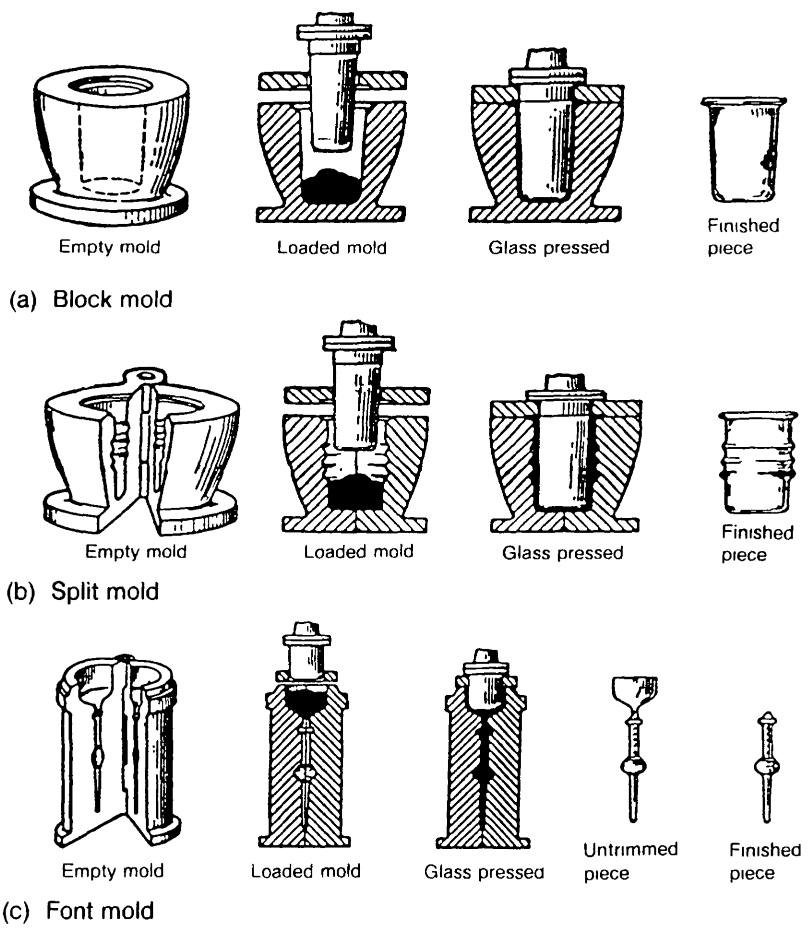


Figure 7

Glass Forming

The material on the lunar surface has a high silicate content. Some of these silicate materials could be the constituents of transparent glasses, which could have a variety of uses at a lunar base. Various processes are available for fabricating objects from glass. Here, molds are used for glass pressing. The liquid glass is poured into the mold, which is compressed. When the glass has cooled, the object is extracted from the mold.

From Shand 1958, p. 164.

Figure 8

Glass Drawing

When silicate glasses are melted, they are viscous and thus can readily be drawn by special machines into fibers or rods or tubes. Glass fiber textiles and mats, which are commonly used terrestrially as thermal and electrical insulators, could be used as construction materials in a space facility.

From Shand 1958, p. 385

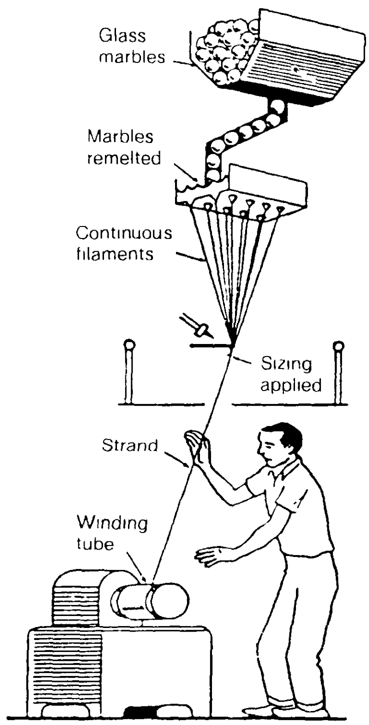
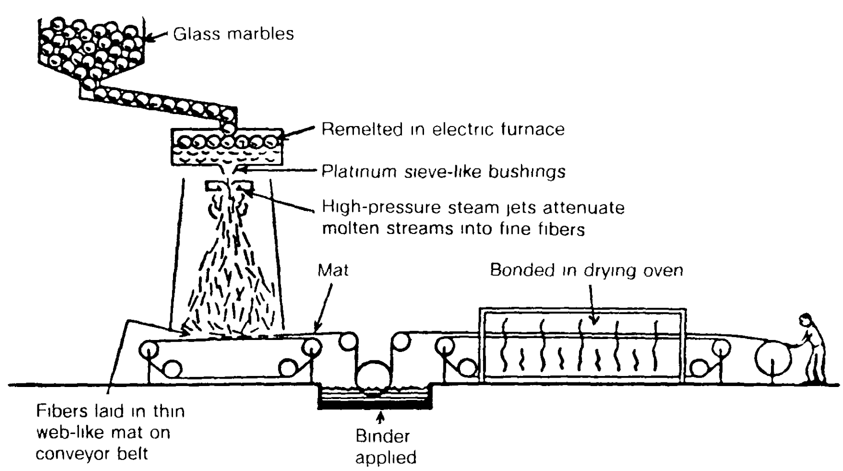


Figure 9

Fiberglass

Another product that could be formed from lunar soil is fiberglass, which might find use as a structural material, perhaps combined with organic or metallic materials. On Earth, fiberglass tanks are commonly used for storage of fluids, such as in standard water heaters.

From Shand 1958, p. 384.



Among the high-leverage uses of fused silicate materials in the proposed utilization of nonterrestrial resources are the fabrication of heat shields for orbital transfer vehicles traveling from the Moon to Earth and the use of sintered or melted and sand-cast soil for structural support in unpressurized lunar shelters. The work of Blacic (1985) indicates that lunar glasses made under the anhydrous, hard-vacuum conditions on the Moon could have very high strengths and thus be quite applicable to structures in space. Prestressed beams made with sintered bricks, using fiberglass or iron bars as tendons, may find early application as structural members.

Ceramics like those used on Earth could be produced by chemical processing of raw lunar material; for example, fractional volatilization of plagioclase could lead to melts for ceramic applications. The recombination of plagioclase with the residue of the ilmenite reduction process (metallic iron and titanium dioxide) could yield cermets with interesting properties. Ceramics might find uses similar to those of glasses.

Alternative means of preparing glasses and ceramics appear to be direct heating using solar concentrators (Ho and Sobon 1979), electrical resistive heating, and microwave heating. Direct use of waste heat from nuclear reactors used in space or on the Moon may also be practical but might require complex heat exchangers, heat pipes, and other devices for thermal control. The microwave heating concept is described in more detail in the first appendix to this part. It offers an efficient means of converting electrical energy into heat, delivered locally and in a controlled manner to the target to be heated. Additional work is necessary to define optimum thermal processing systems for glass and ceramic products and the properties of the heated lunar material. It will be desirable to have access to good simulants of lunar regolith or increased quantities of real lunar soil to further such necessary research.

The production of more complex ceramics, composites, and even semiconductors may prove desirable at some point during the development of a lunar base. Although perhaps not within the scope of most easily obtainable materials, semiconductors produced from lunar materials could have a major effect on the means of producing electricity on the Moon. Silicon-based photovoltaic devices could be constructed using silicon reduced from silicate minerals, covered with thin glass layers made from silicon dioxide, supported by iron, aluminum, or glass structures, and supplied with iron wires to conduct currents. Lunar ilmenite has interesting semiconductor properties (see fig. 10) and might be usable in converting sunlight to electricity. The preparation of photovoltaic devices is now well known on Earth; however, adapting these processes to a lunar environment would be quite challenging.

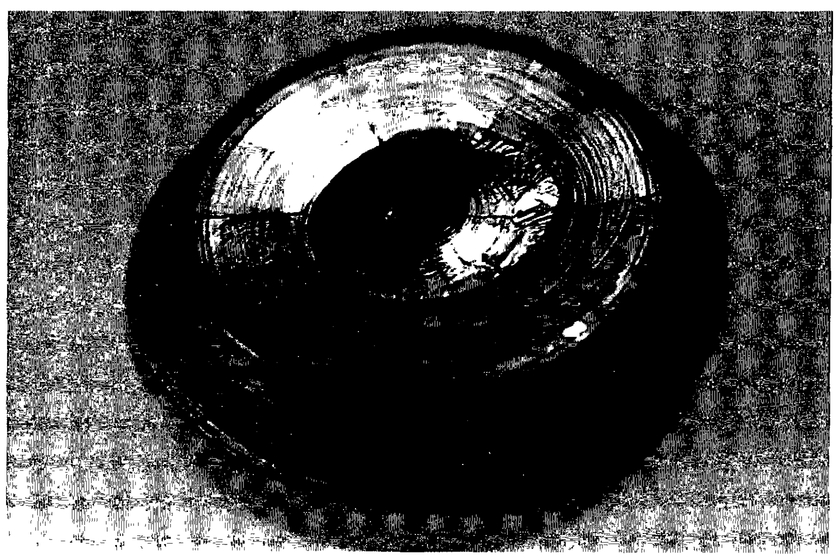


Figure 10

Semiconductors

Lunar ilmenite is a natural semiconductor. Here, a "boule" of ilmenite of lunar composition has been fabricated in a furnace as a single crystal. Cut into thin wafers, provided with electrical leads, and exposed to the Sun, this semiconductor would cause an electrical current to flow. Although rather low in its efficiency of converting light to electricity, ilmenite is so abundant on the Moon that it may be an attractive alternative to photovoltaic devices brought from Earth.

Courtesy of R. K. Pandey, Electronic Materials Laboratory, Texas A&M University, College Station, TX

Cement and Concrete

Gene Corley and Larry A. Haskin

The most commonly used construction material on Earth is concrete made with Portland cement. Three quarters or more of the mass of concrete is aggregate, usually sand and gravel. Portland cement, made by sintering limestone, iron ore, and clay, has as its principal constituents anhydrous calcium silicates and aluminates whose typical compositions are $3CaO \cdot SiO_2$, $2CaO \cdot SiO_2$, $3CaO \cdot Al_2O_3$, and $4CaO \cdot Al_2O_3 \cdot Fe_2O_3$. The first three are essential to good concrete strength. In addition, cured concrete contains about 5 percent (by weight) water, a result of the hydration reactions that bind the Portland cement component around the aggregate.

The principal constituent of concrete—aggregate—is abundant on the lunar surface. Lunar mare basalt is similar to terrestrial basalt, which has been used to make concrete with high compressive strength.

To produce lunar cement, high-temperature processing will be required (see fig. 11). It may be possible to make calcium-rich silicate and aluminate for cement by solar heating of lunar pyroxene and feldspar, or chemical treatment may be required to enrich the calcium and aluminum in lunar soil. The effects of magnesium and ferrous iron present in the starting materials and products would need to be evaluated. So would the problems of grinding to produce cement, mixing, forming in vacuo and low gravity, and minimizing water loss.

The need for water, a substance not known to exist on the Moon [but oxygen is an element in most lunar compounds and see Carter (1985) for the abundance of hydrogen in the lunar soil],

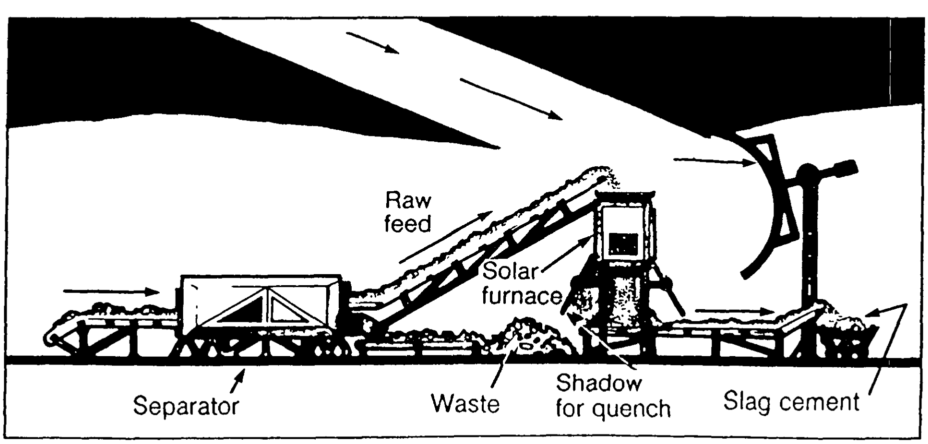


Figure 11

Slag Cement Production Facility

Cement for the concrete might be made by heating lunar anorthitic feldspar to drive off the more volatile components and concentrate its calcium and aluminum oxides. It seems possible to make a usable cement on the lunar surface by relatively simple means. Feedstock separated from lunar soil would be melted in a solar furnace and then quenched in shadow to form a reactive glassy product. When this product is mixed with water and allowed to react and dry, it should make a coherent cement suitable for many structures at a lunar base appears to be the most serious deterrent to extensive use of concrete in space. Nevertheless, the convenience of using concrete in space construction has great potential and such use merits close attention. Water may not always be as scarce a commodity as it is now (see fig. 12), and, for some applications, concrete might prove cost-effective even if water had to be furnished. This possibility becomes more realistic if lunar oxygen is made available so that only hydrogen has to be imported. The hydrogen content of cured concrete can be as low as 0.5 percent (by weight).

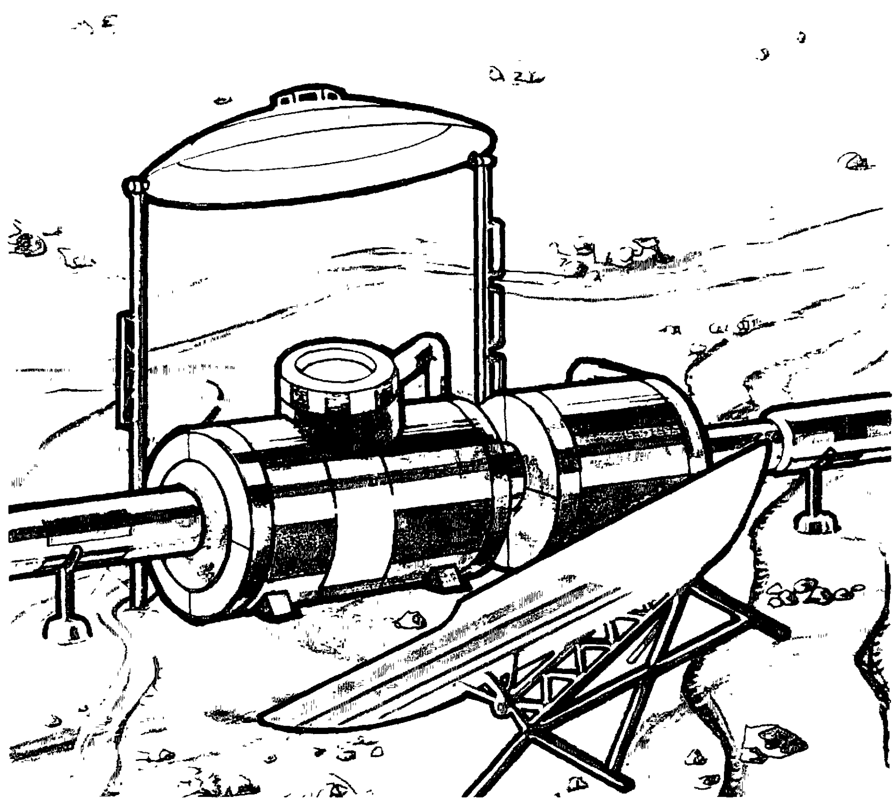


Figure 12

Water on the Moon

Although scarce on the Moon as compared to on Earth, there is enough hydrogen in lunar material to provide about 1 kilogram of water per cubic meter of lunar soil. This water, in turn, could be used to make about 20 kilograms of concrete. The hydrogen could be extracted by solar heating of the finer grained fraction of the lunar regolith, then reacted with ilmenite to form water (and leave an iron-rich residue).

A possible product of interest might be concrete beams reinforced with glass fibers. If imported hydrogen could be used with perfect efficiency, each metric ton could yield 6 kilometers of beams with a cross section of 10 by 10 centimeters. The same amount of hydrogen could yield a wall 10 centimeters thick, 3 meters high, and 24 meters long. Thus, where bulk plus reasonable strength is required or where complex shapes are needed, concrete may be a plausible material to use. See figure 13.

A more complete discussion of concrete's properties and potential uses is found in the second appendix to this part.

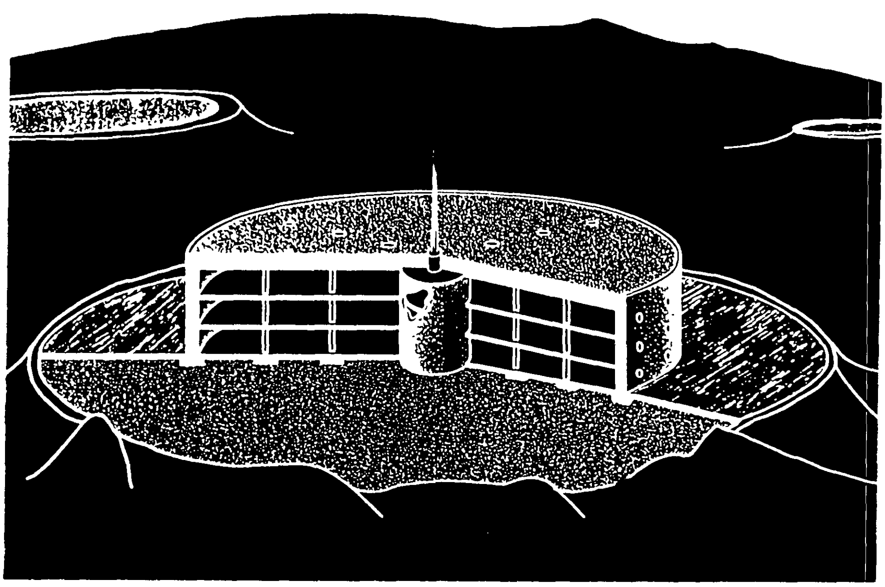


Figure 13

Concrete Structure

Concrete can be made from rocks, sand, cement, and water. The rocks and sand are readily available on the lunar surface. Cement could be made from lunar soil, although considerable processing would be required to produce the right composition. Even the hydrogen for the water might be found in the lunar soil

The facility shown here, which could house 300 people, would require about 36 metric tons of hydrogen, to be brought from Earth. All other constituents of the concrete would be lunar. If the same 36 metric tons were brought from Earth in the form of space station modules, the assembled structure would provide space for only 8-10 people.

Application of Manufactured Products

Sankar Sastri and Michael B. Duke

As table 3 shows, a wide range of useful products can, in principle, be manufactured from the following materials:

1. Lunar regolith or basalt
2. Regolith or rock beneficiated to concentrate plagioclase or other minerals
3. Iron, extracted from lunar soil or rocks by various means
4. Naturally occurring or easily obtained materials that have cementitious properties
5. Byproducts of the above products

TABLE 3. *Products Derived From Lunar Materials*

	Sintered regolith	Glass and ceramics	Cement	Metal
(a) Basic construction materials and their sources				
Beams	X	X	X	X
Plates, sheets	X	X	X	X
Transparent plates (windows)	–	X	–	–
Bricks, blocks	X	X	X	–
Pipes, tubes	–	X	X	X
Low-density materials (foams)	–	X	–	–
Fiber, wires, cables	–	X	–	X
Foils, reflective coatings	–	–	–	X
Hermetic seals (coatings)	–	X	X	X
Formed objects	–	X	–	X

TABLE 3 *(concluded)*.

	Sintered regolith	Glass and ceramics	Cement	Metal
(b) Applications and their parts, listed under their source materials				
Aerobraking heat shields		Low-density thermal protection material		Structural beams
Pressurized habitats	Radiation protection, insulation	Windows, seals	Internal structural plates (floors), beams	Pressure vessels, tanks
Photovoltaic arrays		Semiconductors	Foundation structure	Support structure, wires
Agricultural systems	Radiation protection, insulation	Windows, seals, high-pressure pipes	Structure, low-pressure pipes	Tanks, machine parts, wires

In addition to oxygen, which can be obtained by several processes, either from unbeneficiated regolith or by reduction of concentrated ilmenite, these materials make the simplest requirements of the lunar resource extraction system. A thorough analysis of the impact of these simplest products on the economics of space operations is not possible at this point. Research is necessary both to define optimum techniques and adapt them to space and to determine the probable market for the products so that the priority of various processes can be assessed.

However, as figures 14-17 show, we can envision simple to quite complex construction projects on the lunar surface even in the early stages of lunar operation. And the growth of an industry to make lunar products for use off the Moon is a possibility, though a more distant one.

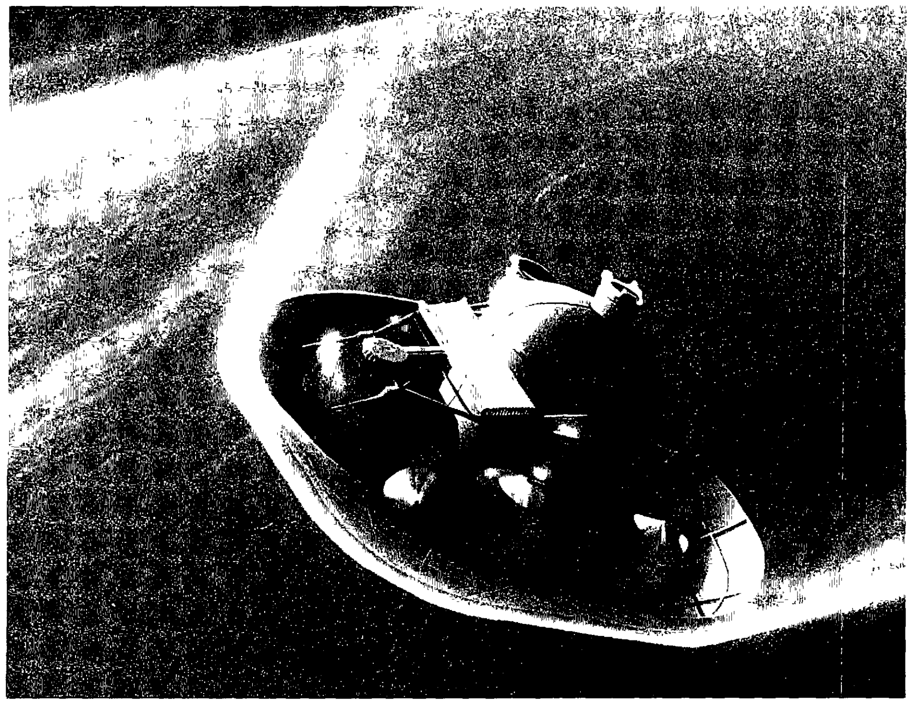
Figure 14

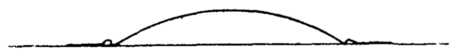
Aerobraking Heat Shields

When spacecraft, such as the Space Shuttle, enter the atmosphere of a planet at high velocity, the frictional heat must be dissipated and the interior of the spacecraft protected from high temperature. The thermal protection system of the Space Shuttle consists of reusable glass tiles, made out of silicon dioxide, which have very low thermal conductivity and remove the heat by radiation, conduction, and convection in the atmosphere. In contrast, the Apollo heat shield was an ablatable structure, the exterior of which melted and was sloughed off as the spacecraft reentered.

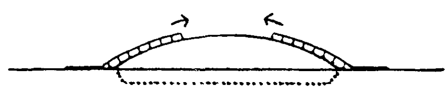
The principal components of these heat shields are a supporting structure and the thermal protection material itself. If lunar material can be used to make heat shields (either reusable or ablatable), the cost of transporting such shields to the Moon can be avoided. This could significantly reduce the cost of transporting lunar products to Earth.

Artist: Doug McLeod

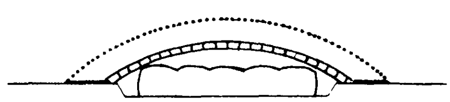




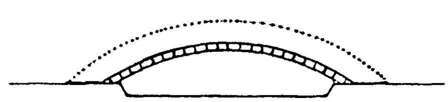
1. Inflated arch support form



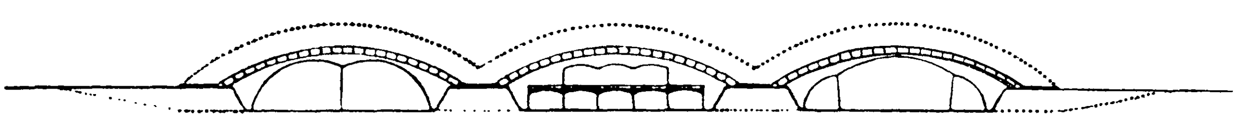
2. Interlocking, molded regolith arch components laid over inflated form



3. Regolith pushed over arch, pneumatic support form removed, area underneath excavated where required by dragline scoop, and pressurized enclosures erected



4. Alternative pressurized enclosure using hermetic membrane applied to inner surface of shield



5. Interconnected arch shields with range of pressurized enclosures

Figure 15

Pressurized Habitats

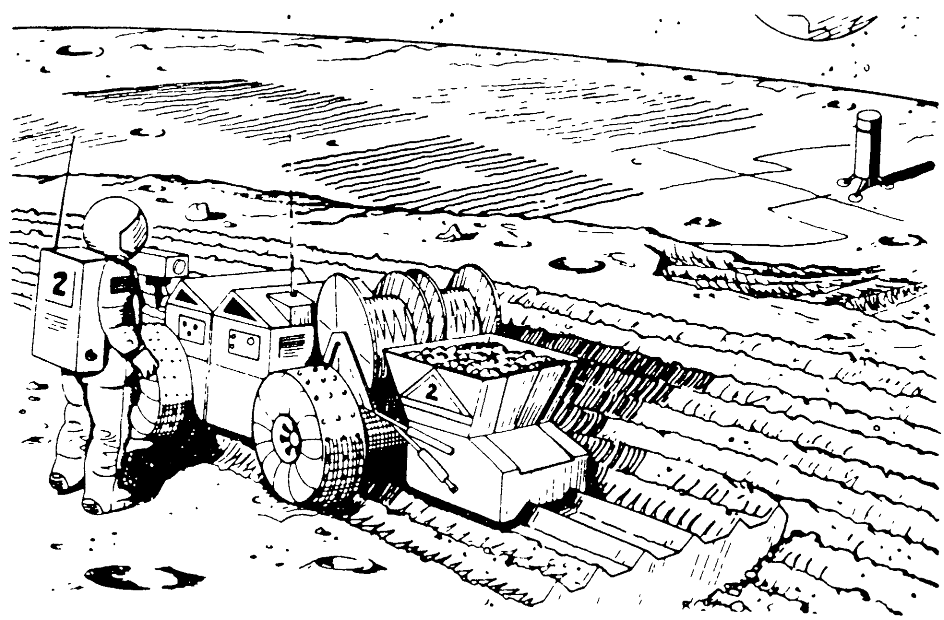
The ability to construct hermetically sealed habitats from lunar materials could lead to rapid expansion of lunar capabilities. This illustration shows the construction of a dome-shaped structure using 2-meter-thick sintered regolith blocks, which serve as radiation shielding. (Each block has a mass that would weigh 15 metric tons on Earth, 2-1/2 metric tons on the Moon.) This structure would require an airtight seal, which might be provided by the application of a melted silicate glaze. Alternatively, lightweight organic seals could be brought from Earth. Internal structure—floors, walls, beams—could be made from metal, glass, or concrete.

Taken from Land 1985, p. 368

Figure 16

Lunar Photovoltaic Farms

A combination of items manufactured on the Moon might be used to produce a lunar power system. Photovoltaic semiconductor materials are deposited on prepared ridges in the lunar soil. Iron wires will carry the electricity to microwave transmitters. Microwave reflectors consisting of lunar ceramic and iron wires can beam the microwaves to space, even all the way to Earth. Thus, a relatively small lunar processing facility can rapidly develop substantial quantities of electricity using primarily indigenous materials.



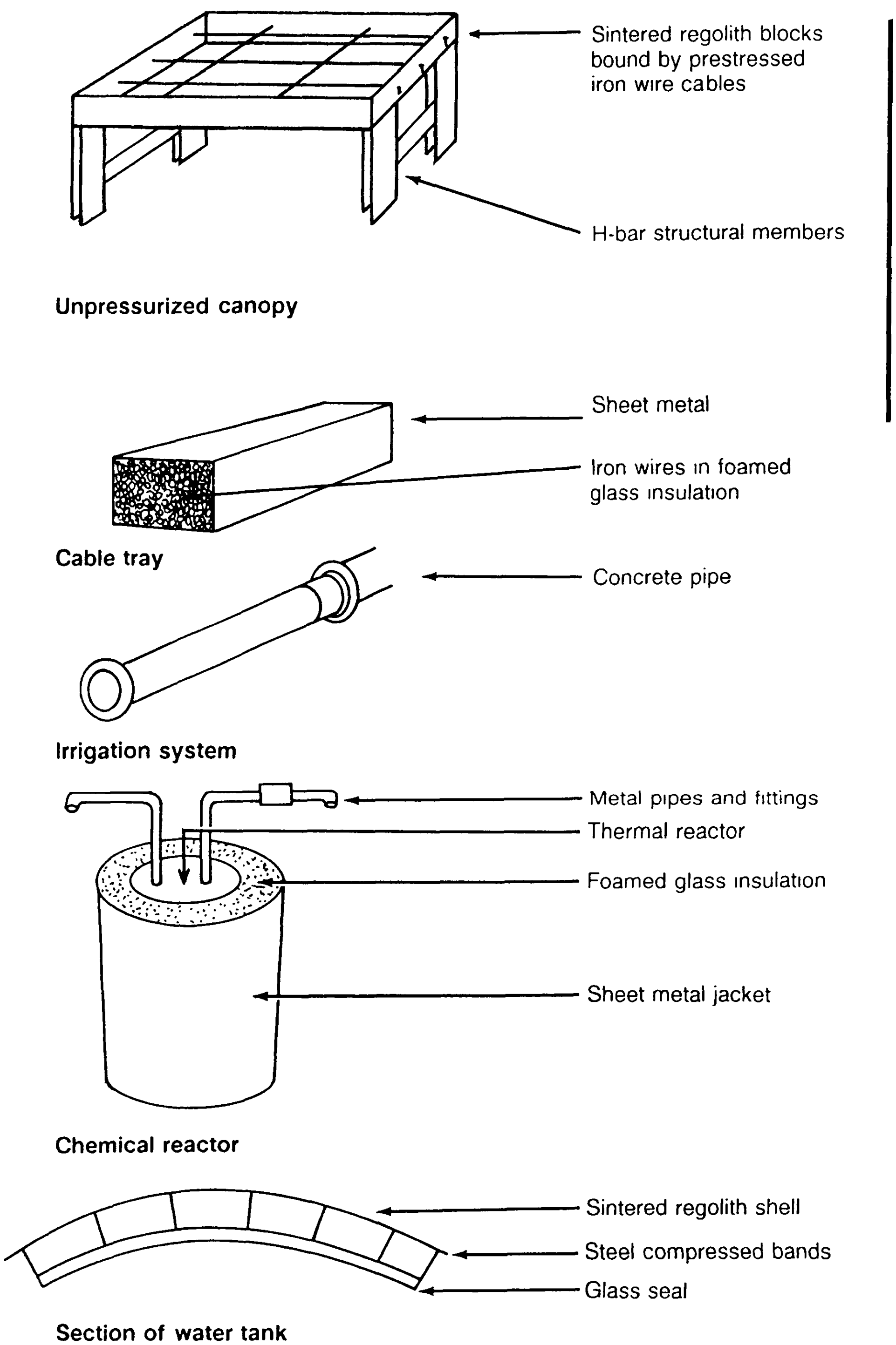


Figure 17

Agricultural Systems

Many applications of lunar materials could be found in a "home-grown" lunar agriculture facility. Structural members are similar to those for the habitat described in figure 15. Internal plumbing—tanks and pipes—could be made from glass, metal, or concrete. Plants may be grown in modified lunar soil. The lunar farm is also an essential component of the environmental control system for the lunar base, purifying air and water.

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Appendix A: Microwave Heating of Lunar Materials

Thomas T. Meek

Introduction

Microwave heating of nonmetallic inorganic material has been of interest for many years. Von Hippel in the late 1940s and early 1950s investigated how microwave radiation up to 10 GHz couples to various insulator materials. Perhaps the most work has been done by Wayne Tinga at the University of Edmonton (Alberta, Canada). Most of the work to date has been done at the two frequency bands allowed in industrial use (0.915 GHz and 2.45 GHz). However, some work has recently been carried out at 28 GHz* and 60 GHz (Meek et al. 1986). At Los Alamos National Laboratory, the work has centered about the fabrication of useful engineering components.

Table A-1 lists some materials that have been thermally processed using microwave energy and some products that have been fabricated at both 2.45 GHz and 60 GHz.

*Personal communication with H. D. Kimrey, Fusion Energy Division, Oak Ridge National Laboratory.

TABLE A-1. *Some Starting Materials Heated by Microwave Energy at Los Alamos and Resultant Products*

Material	Product	Processing temperature, °C	Frequency, GHz
Owens-Illinois (OI)—1756C glass	Ceramic-glass seal	462	2.45
OI—0038 glass	Ceramic-glass seal	735	2.45
1613 glass**	Ceramic-glass seal	1450	2.45
Alkali basalt	Sintered material	1200	2.45
Al_2O_3	Sintered material	1300-1900	2.45, 60
ZrO_2	Sintered material	1300-1900	2 45, 60
Ilmenite	Sintered material	1350	2 45
Apollo 11 regolith	Sintered material	1100	60
SiC whisker-Al_2O_3	Composite material	1300-1900	2.45, 60

**High-temperature glass made at Los Alamos

Using microwave energy to process lunar material offers a new, potentially very efficient way of heating these types of materials. Not only can lunar material be heated with less energy than that required by conventional methods, but the heating is accomplished more uniformly and in much less time (Meek et al. 1985).

Discussion

Many oxide materials are transparent to microwave energy at 2.45 GHz and 0.915 GHz. Oxides that possess impurities, such as mobile ions or mobile defects, that enhance their electrical conductivity will, however, couple to electromagnetic radiation in this frequency range. Heating will be primarily electronic.

For example, beta alumina contains by weight 11 percent sodium, thus enabling it to couple efficiently to 2.45 GHz microwave radiation. Beta alumina, when placed in a 2.45 GHz microwave field of 400 watts power can be heated from room temperature to its sintering temperature (1850°C) in just a few seconds (Berteand and Badot 1976). Materials such as cuprous oxide (Cu_2O), zinc oxide (ZnO), and zirconium dioxide (ZrO_2) will also couple efficiently because they are defect-controlled semiconductors. To heat traditional oxide materials, such as alpha alumina, we incorporate materials that do couple to 2.45 GHz radiation, such as aluminum nitrate. These materials cause the oxide to heat to a few 100 degrees Celsius, after which the oxide will couple because its ability to absorb electromagnetic energy (its loss tangent) has increased sufficiently.

It is known that most lunar regolith, down to a depth of 3 meters, contains at least 10^6 imperfections per cubic centimeter from cosmic rays, solar flares, and the solar wind (see fig. A-1). The defects introduced into this soil over millions of years' exposure to these high-energy particles should increase the loss tangent of this material and allow it to be heated in a microwave field without the use of coupling agents. Terrestrial alkali basalt shows only weak coupling initially; however, when the intensity of the electric field is increased, this material heats rapidly. Recently we demonstrated the ability to heat ilmenite to its melting temperature using 2.45 GHz microwave energy. Since ilmenite is present in abundance on the lunar surface in mare regions, it could act as a coupling agent to allow the initial heating of those lunar materials that may not couple at ambient temperature.

Figure A-1

Tracks of Cosmic Ray Particles and Solar Flare Particles in a Plagioclase Crystal

The plagioclase crystal structure has been severely damaged where these high-energy particles have penetrated into the crystal. Etching of the crystal with NaOH has preferentially removed the damaged material, leaving elongated, rectangular holes or tracks. Such track damage is common in many lunar regolith crystals

Table A-2 shows observed heating rates for some of the materials thermally processed using 2.45 GHz and 60 GHz microwave energy. If the proper electric field intensity (E) or magnetic field intensity (H) is used, rapid heating of lunar materials will also occur. The following expression (Püschner 1966) shows the relationship between the approximate heating rate and the applied electric field intensity for the heating of an insulator material.

$$\dot{T} = \frac{8 \times 10^{-12} f E^2 k' \tan \delta}{\rho C_p}$$

where $\dot{T}$ = heating rate in degrees Celsius per minute
f = frequency in hertz
E = electric field intensity in volts/cm
k' = dielectric constant of the material
$\tan \delta$ = loss tangent of the material
ρ = density of the material
C_p = heat capacity of the material

Because heating on the Moon will occur in a vacuum, where much greater electric field intensities can be used, materials that would not couple on Earth may be heated very easily and quickly.

TABLE A-2. *Heating Rates Observed for Different Insulator Materials Heated at 2.45 GHz and 60 GHz*

Material	Observed heating rate, °C per hour	Frequency, GHz
1613 glass	33 000	2.45
OI–0038 glass	20 000	2.45
OI–1756C glass	12 000	2.45
Aluminum oxide	18 000	60

Recommendations

Much work remains to fully characterize some of the phenomena observed to date with microwave-heated oxide and composite materials. For example, diffusion should be modeled, reaction kinetics should be studied, and sintering kinetics should be better understood.

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Appendix B: Properties and Uses of Concrete

Gene Corley

Properties of Concrete

Concretes that can now be formed have properties which may make them valuable for lunar or space construction. These properties include high compressive strength, good flexural strength (when reinforced), and favorable responses to temperature extremes (even increased strength at low temperatures). These and other properties of concrete are described in T. D. Lin's contribution to this report ("Concrete: Potential Material for Space Station").

Higher quality cements and products may become possible. Among other possibilities is manufacture of "zero-macro-defect" concrete products. When manufactured on Earth, these materials have the potential for developing a tensile strength of 15 000 psi [103 megapascals (MN/m^2)] and a compressive strength of 30 000 psi (207 MN/m^2). Although they are made at relatively low temperatures and pressures, they have properties similar to those of some ceramics.

Other properties of concrete that make its application attractive are good radiation absorption and stability at high temperature. Porosity and permeability may be a problem, necessitating the addition of impermeable coatings in some applications.

Fabrication Techniques

Procedures common on Earth can be used to fabricate structural products. The following techniques are possible:

1. Casting
2. Curing at ordinary temperatures or autoclaving
3. Shotcreting with glass fiber reinforcements

Of the techniques available, autoclaving appears most attractive for "high strength" products. This can be done by placing molded concrete units in a pressure vessel painted black on one side. Curing can be accomplished within a few hours. All free water can be recaptured for reuse. Autoclaving will accelerate the cure and produce concretes that contain less combined water than products cured at low temperatures and have greater volume stability upon drying, which are advantages in the space environment. Slag-type silicate-based hydraulic cements are well suited to autoclaving, because the high temperatures accelerate the hydration reactions.

Shotcreting can be used to construct large monolithic structures. Pressure vessels, structured shapes, floor slabs, and wall panels can be fabricated with the use of glass fiber reinforcements. Molds made of inflated membranes can be used for large enclosures. As in the case of autoclaving, free moisture can be recaptured.

For some applications, such as patching or grouting, where conditions make special curing impossible, a relatively quick-setting cement might be needed. Portland cements are not well suited to such applications, but phosphate cements could be developed to meet such needs. Sulfur cements, which do not require water, have been suggested, but they have poorer properties than hydraulic cements. Special composition cements are a topic worthy of further research.

On the Moon, buildings made of concrete and sheltered by a soil covering can be used as space for living, manufacturing, and storage. The amount of energy used in concrete construction can be low, and the level of worker skill does not need to be high for good results.

As concrete processing technology using appropriate lunar materials develops, concrete may find application in Earth orbit for construction of large structures (see T. D. Lin's paper). Concrete materials such as aggregate, cement, and oxygen from the Moon and hydrogen from Earth can be transported and, in advanced scenarios, at competitive transportation costs. Where large masses of material are desired, concrete has the advantage over unprocessed or sintered material in that it can be cast into compartmented but monolithic structures of high strength, using lightweight forms (e.g., inflated impermeable membranes). Indeed, the versatility of concrete for construction on Earth may be matched in space.

Addendum: Participants

The managers of the 1984 summer study were

David S. McKay, Summer Study Co-Director and Workshop Manager
Lyndon B. Johnson Space Center

Stewart Nozette, Summer Study Co-Director
California Space Institute

James Arnold, Director
of the California Space Institute

Stanley R. Sadin, Summer Study Sponsor
for the Office of Aeronautics and Space Technology
NASA Headquarters

Those who participated in the 10-week summer study as faculty fellows were the following:

James D. Burke	Jet Propulsion Laboratory
James L. Carter	University of Texas, Dallas
David R. Criswell	California Space Institute
Carolyn Dry	Virginia Polytechnic Institute
Rocco Fazzolare	University of Arizona
Tom W. Fogwell	Texas A & M University
Michael J. Gaffey	Rensselaer Polytechnic Institute
Nathan C. Goldman	University of Texas, Austin
Philip R. Harris	California Space Institute
Karl R. Johansson	North Texas State University
Elbert A. King	University of Houston, University Park
Jesa Kreiner	California State University, Fullerton
John S. Lewis	University of Arizona
Robert H. Lewis	Washington University, St. Louis
William Lewis	Clemson University
James Grier Miller	University of California, Los Angeles
Sankar Sastri	New York City Technical College
Michele Small	California Space Institute

Participants in the 1-week workshops included the following:

Constance F. Acton	Bechtel Power Corp.
William N. Agosto	Lunar Industries, Inc.
A. Edward Bence	Exxon Mineral Company
Edward Bock	General Dynamics
David F. Bowersox	Los Alamos National Laboratory
Henry W. Brandhorst, Jr.	NASA Lewis Research Center
David Buden	NASA Headquarters
Edmund J. Conway	NASA Langley Research Center
Gene Corley	Portland Cement Association
Hubert Davis	Eagle Engineering
Michael B. Duke	NASA Johnson Space Center
Charles H. Eldred	NASA Langley Research Center
Greg Fawkes	Pegasus Software
Ben R. Finney	University of Hawaii
Philip W. Garrison	Jet Propulsion Laboratory
Richard E. Gertsch	Colorado School of Mines
Mark Giampapa	University of Arizona
Charles E. Glass	University of Arizona
Charles L. Gould	Rockwell International
Joel S. Greenberg	Princeton Synergetics, Inc.
Larry A. Haskin	Washington University, St. Louis
Abe Hertzberg	University of Washington
Walter J. Hickel	Yukon Pacific
Christian W. Knudsen	Carbotek, Inc.
Eugene Konecci	University of Texas, Austin
George Kozmetsky	University of Texas, Austin
John Landis	Stone & Webster Engineering Corp.
T. D. Lin	Construction Technology Laboratories
John M. Logsdon	George Washington University
Ronald Maehl	RCA Astro-Electronics
Thomas T. Meek	Los Alamos National Laboratory
Wendell W. Mendell	NASA Johnson Space Center
George Mueller	Consultant
Kathleen J. Murphy	Consultant
Barney B. Roberts	NASA Johnson Space Center
Sanders D. Rosenberg	Aerojet TechSystems Company
Robert Salkeld	Consultant
Donald R. Saxton	NASA Marshall Space Flight Center
James M. Shoji	Rockwell International
Michael C. Simon	General Dynamics
William R. Snow	Electromagnetic Launch Research, Inc.
Robert L. Staehle	Jet Propulsion Laboratory
Frank W. Stephenson, Jr.	NASA Headquarters
Wolfgang Steurer	Jet Propulsion Laboratory
Richard Tangum	University of Texas, San Antonio
Mead Treadwell	Yukon Pacific
Terry Triffet	University of Arizona
J. Peter Vajk	Consultant
Jesco von Puttkamer	NASA Headquarters
Scott Webster	Orbital Systems Company
Gordon R. Woodcock	Boeing Aerospace Company

The following people participated in the summer study as guest speakers and consultants:

Edwin E. "Buzz" Aldrin	Research & Engineering Consultants
Rudi Beichel	Aerojet TechSystems Company
David G. Brin	California Space Institute
Joseph A. Carroll	California Space Institute
Manuel I. Cruz	Jet Propulsion Laboratory
Andrew H. Cutler	California Space Institute
Christopher England	Engineering Research Group
Edward A. Gabris	NASA Headquarters
Peter Hammerling	LaJolla Institute
Eleanor F. Helin	Jet Propulsion Laboratory
Nicholas Johnson	Teledyne Brown Engineering
Joseph P Kerwin	NASA Johnson Space Center
Joseph P Loftus	NASA Johnson Space Center
Budd Love	Consultant
John J. Martin	NASA Headquarters
John Meson	Defense Advanced Research Projects Agency
Tom Meyer	Boulder Center for Science and Policy
John C. Niehoff	Science Applications International
Tadahiko Okumura	Shimizu Construction Company
Thomas O. Paine	Consultant
William L. Quaide	NASA Headquarters
Namika Raby	University of California, San Diego
Donald G. Rea	Jet Propulsion Laboratory
Gene Roddenberry	Writer
Harrison H. "Jack" Schmitt	Consultant
Richard Schubert	NASA Headquarters
Elie Shneour	Biosystems Associates, Ltd.
Martin Spence	Shimizu Construction Company
James B. Stephens	Jet Propulsion Laboratory
Pat Sumi	San Diego Unified School District
Robert Waldron	Rockwell International
Simon P Worden	Department of Defense
William Wright	Defense Advanced Research Projects Agency

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SPACE RESOURCES

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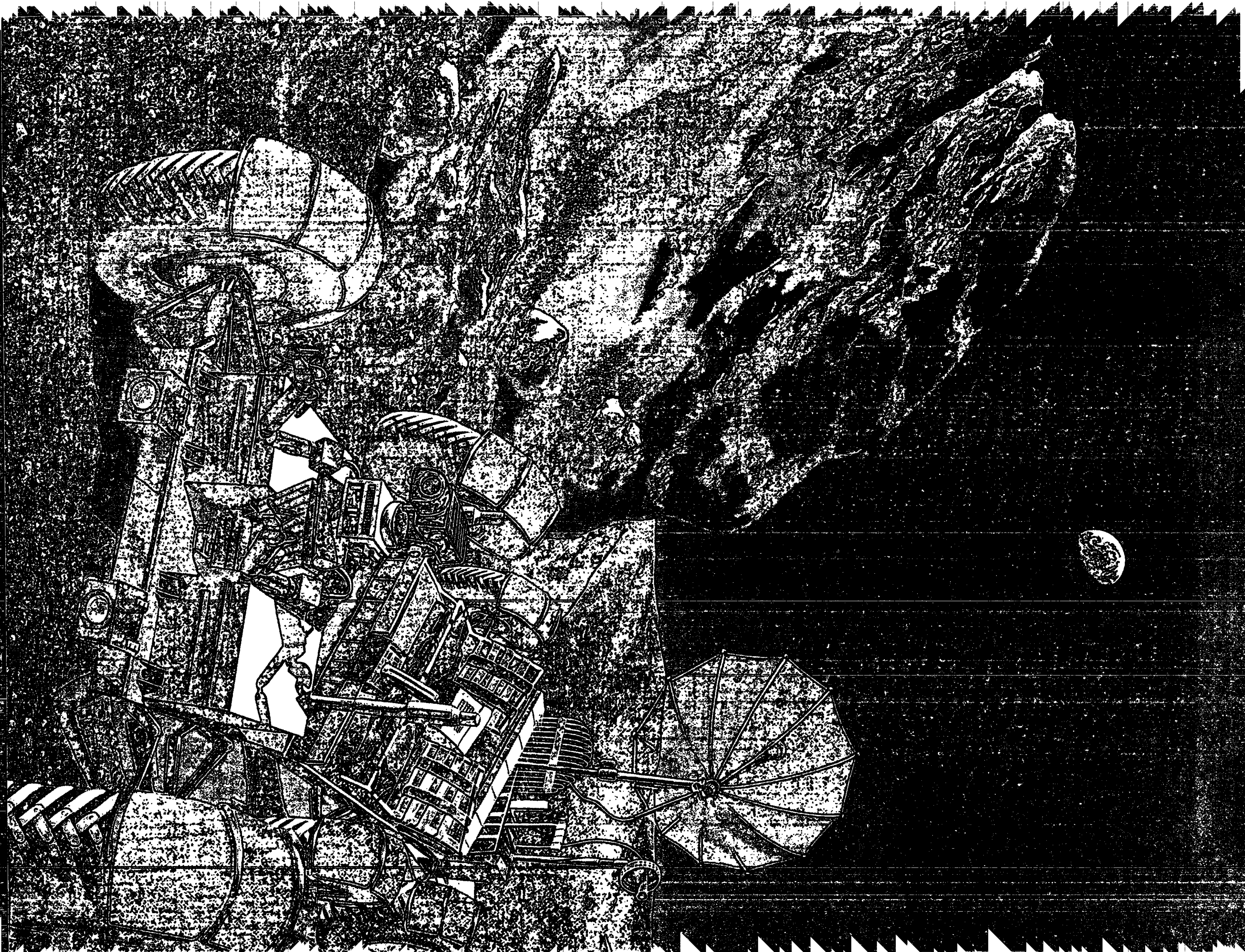

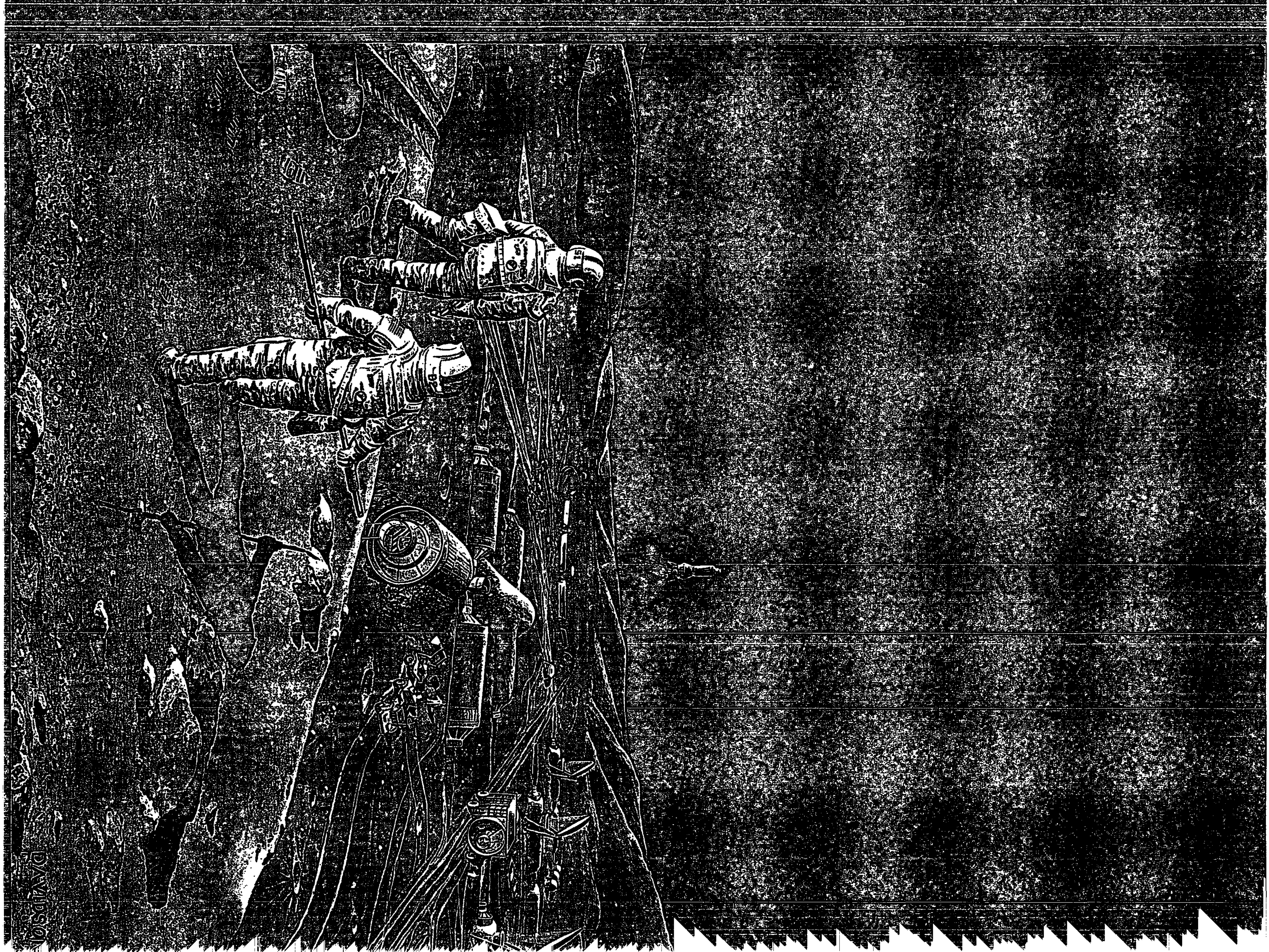
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Frontispiece

Advanced Lunar Base

In this panorama of an advanced lunar base, the main habitation modules in the background to the right are shown being covered by lunar soil for radiation protection. The modules on the far right are reactors in which lunar soil is being processed to provide oxygen. Each reactor is heated by a solar mirror. The vehicle near them is collecting liquid oxygen from the reactor complex and will transport it to the launch pad in the background, where a tanker is just lifting off. The mining pits are shown just behind the foreground figure on the left. The geologists in the foreground are looking for richer ores to mine.

Artist: Dennis Davidson

NASA SP-509, vol. 4

Space Resources

Social Concerns

Editors

Mary Fae McKay, David S. McKay, and Michael B. Duke

Lyndon B. Johnson Space Center
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Preface

Space resources must be used to support life on the Moon and exploration of Mars. Just as the pioneers applied the tools they brought with them to resources they found along the way rather than trying to haul all their needs over a long supply line, so too must space travelers apply their high technology tools to local resources.

The pioneers refilled their water barrels at each river they forded; moonbase inhabitants may use chemical reactors to combine hydrogen brought from Earth with oxygen found in lunar soil to make their water. The pioneers sought temporary shelter under trees or in the lee of a cliff and built sod houses as their first homes on the new land; settlers of the Moon may seek out lava tubes for their shelter or cover space station modules with lunar regolith for radiation protection. The pioneers moved further west from their first settlements, using wagons they had built from local wood and pack animals they had raised; space explorers may use propellant made at a lunar base to take them on to Mars.

The concept for this report was developed at a NASA-sponsored summer study in 1984. The program was held on the Scripps campus of the University of California at San Diego (UCSD), under the auspices of the American Society for Engineering Education (ASEE). It was jointly managed by the California Space Institute and the Lyndon B. Johnson Space Center, under the direction of the Office of Aeronautics and Space Technology (OAST) at NASA Headquarters. The study participants (listed in the addendum) included a group of 18 university teachers and researchers (faculty fellows) who were present for the entire 10-week period and a larger group of attendees from universities, Government, and industry who came for a series of four 1-week workshops.

The organization of this report follows that of the summer study. *Space Resources* consists of a brief overview and four detailed technical volumes: (1) Scenarios; (2) Energy, Power, and Transport; (3) Materials; (4) Social Concerns. Although many of the included papers got their impetus from workshop discussions, most have been written since then, thus allowing the authors to base new applications on established information and tested technology. All these papers have been updated to include the authors' current work.

This volume—Social Concerns—covers some of the most important issues which must be addressed in any major program for the human exploration of space. The volume begins with a consideration of the economics and management of large-scale space activities. Then the legal aspects of these activities are discussed, particularly the interpretation of treaty law with respect to mining the Moon and asteroids. The social and cultural issues of moving people into space are considered in some detail, and the eventual emergence of a space culture different from our existing culture is envisioned. The environmental issues raised by the development of space settlements are faced. Finally, the authors of this volume, which concludes the report *Space Resources*, propose some innovative approaches to space communities and habitats and consider self-sufficiency and human safety at a lunar base or outpost.

This is certainly not the first report to urge the utilization of space resources in the development of space activities. In fact, *Space Resources* may be seen as the third of a trilogy of NASA Special Publications reporting such ideas arising from similar studies. It has been preceded by *Space Settlements: A Design Study* (NASA SP-413) and *Space Resources and Space Settlements* (NASA SP-428).

And other, contemporaneous reports have responded to the same themes. The National Commission on Space, led by Thomas Paine, in *Pioneering the Space Frontier*, and the NASA task force led by astronaut Sally Ride, in *Leadership and America's Future in Space*, also emphasize expansion of the space infrastructure; more detailed exploration of the Moon, Mars, and asteroids; an early start on the development of the technology necessary for using space resources; and systematic development of the skills necessary for long-term human presence in space.

Our report does not represent any Government-authorized view or official NASA policy. NASA's official response to these challenging opportunities must be found in the reports of its Office of Exploration, which was established in 1987. That office's report, released in November 1989, of a 90-day study of possible plans for human exploration of the Moon and Mars is NASA's response to the new initiative proposed by President Bush on July 20, 1989, the 20th anniversary of the Apollo 11 landing on the Moon: "First, for the coming decade, for the 1990s, Space Station *Freedom*, our critical next step in all our space endeavors. And next, for the new century, back to the Moon, back to the future, and this time, back to stay. And then a journey into tomorrow, a journey to another planet, a manned mission to Mars." This report, *Space Resources*, offers substantiation for NASA's bid to carry out that new initiative.

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Synthesis of Space Activities 1985–2010*

The next 25 years will bring a new era in space development. Presidential policy confirms that the United States of America through its National Aeronautics and Space Administration is committed to the establishment of a permanent human presence in space.

Space-based resources offer new opportunities to make that goal achievable. Research into and development of space-based resources will give the nation additional scientific and economic leverage, while the involvement of more people in such space operations will improve human performance aloft and the quality of life on Earth.

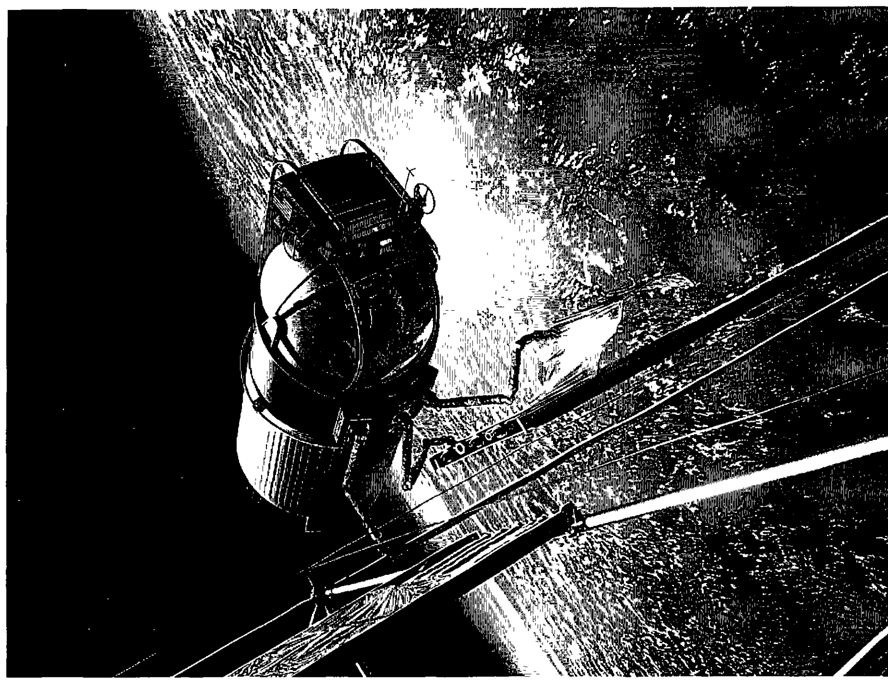
The extension of human capabilities on the space frontier can be accomplished through a combination of human and automated activities. That is, by the extended presence of humans on a space station, by the use of robots at a manned lunar outpost, by automated and manned exploration of Mars, and by unmanned probes into the solar system. Such activities by 2010 provide a necessary springboard for further exploration and exploitation of space resources, such as on the asteroids and on Mars.

*This statement was prepared by faculty fellows Philip R. Harris, Carolyn Dry, Nathan C. Goldman, Karl R. Johansson, Jesa Kreiner, Robert H. Lewis, and James Grier Miller, assisted by workshop participants Ben R. Finney, Ronald Maehl, Kathleen J. Murphy, Namika Raby, Michael C. Simon, Richard Tangum, and J. Peter Vajk and consultants David G. Brin and Elie Shneour. These observations were made in 1984. Subsequent events, especially the reports in 1986 of the National Commission on Space *(Pioneering the Space Frontier)* and the Presidential Commission on the Space Shuttle Challenger Accident, seem to confirm their relevance.

A Combination of Human and Automated Activities

Secured to a strut of Space Station Freedom, a robotic construction vehicle maneuvers a sheet of thermal insulating foil at the command of an astronaut inside. The pressurized vehicle (which on dangerous missions need not be piloted) will be able to build large structures as well as perform delicate microelectronic repairs. Computers, communications equipment, lights, and cameras will be housed in its upper section; the lower portion will hold life support and electrical systems. Such a robot, piloted or teleoperated, represents the combination of human and automated activities that our group thinks will best accomplish the goals of assembling a space station, building a base on the Moon, and mounting an expedition to Mars.

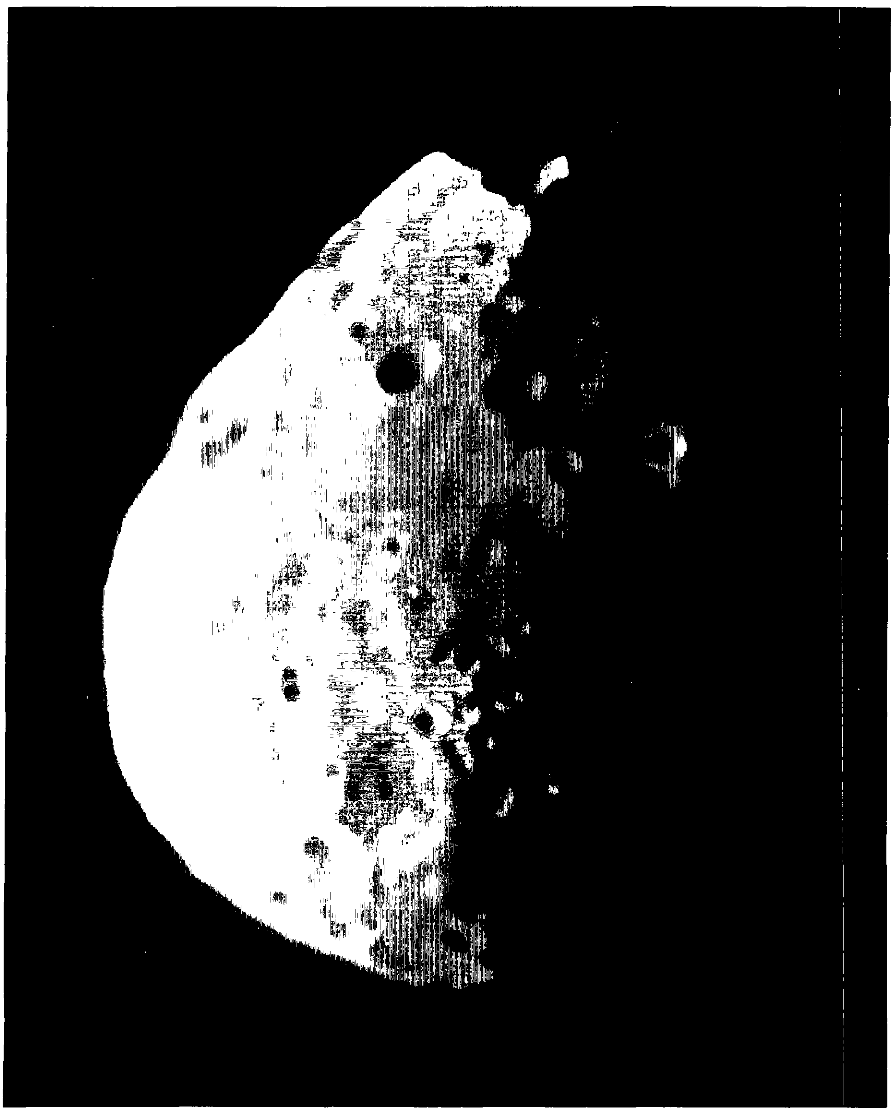
Courtesy of the artist, Paul Hudson, and of the spacecraft designer, Brand Griffin



To stay on the "high ground," beginning with utilization of near-Earth resources, requires a long-term view of the benefits to humankind. Furthermore, an expanded infrastructure needs to be developed both on Earth and in space, first in low Earth orbit (LEO) and then in geosynchronous orbit (GEO). To achieve such objectives will require the development of bases at multiple locations in space, with more complexity and greater numbers and varieties of people on them.

Therefore, NASA should be encouraged in the short term to pursue the opportunities for space industrialization provided by a permanent space station and platform, as well as to develop the necessary technology and plans for a lunar outpost and possibly for an asteroid expedition. In this process, it is vital that support be given to research into ecological life support systems and ergonomics in space.

Over the long term—25-100 years—strategic planning should include taking advantage of the resources on the asteroids and on Mars, as well as unmanned exploration of other suitable locations in the cosmos.



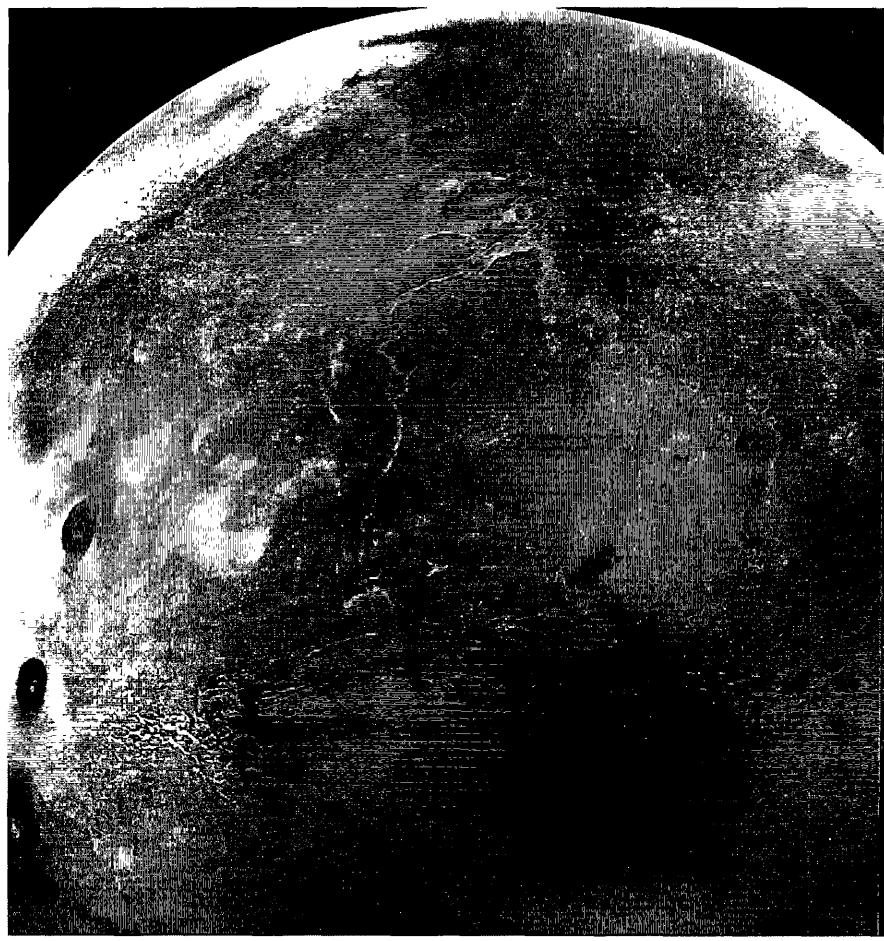
Phobos

This is the first Viking 1 Orbiter 1 picture of Phobos, one of the two moons of Mars The irregularly shaped satellite is thought by many to be a captured asteroid. North is at the top of the picture, while the point of Phobos which always points towards Mars is at the lower left. The large crater near the north pole is approximately 5 km across. The diameter of Phobos when viewed from this angle is about 22 km Only about half of the surface of Phobos facing the camera was illuminated. The low density and dark albedo of Phobos make some scientists suspect that it has the composition of carbonaceous chondrite meteorites. If so, chemically bound water should be plentiful

Mars

This mosaic, composed of 102 Viking Orbiter images, covers nearly a full hemisphere of Mars (the smallest observable feature is about 1 km across). The center of the scene shows the entire Valles Marineris canyon, over 3000 km long (about 10 times as long as Earth's Grand Canyon) and up to 8 km deep. A bright patch of white material in the eastern extremity of the canyon may consist of carbonates deposited in an ancient lake Water appears to have flowed from east to west through the Valles Marineris and from south to north up the bright Kasei Vallis (not surficially connected to Valles Marineris) to the dark basin called the Acidalia Planitia at the top of this picture. The dark spots to the west are three of the Tharsis volcanoes, each about 25 km high (twice as high as Mount Everest). When these images were acquired by Viking 1 Orbiter 1 in 1980, the atmosphere was relatively dust-free. The white streaks, best seen in the lower left quadrant, and the hazes elsewhere are clouds, which probably consist of water ice. The resources suggested by the interpretation of this photomosaic—carbonates, volcanic gases, water ice—will be important in the development of a colony on Mars.

Photo: U.S. Geological Survey

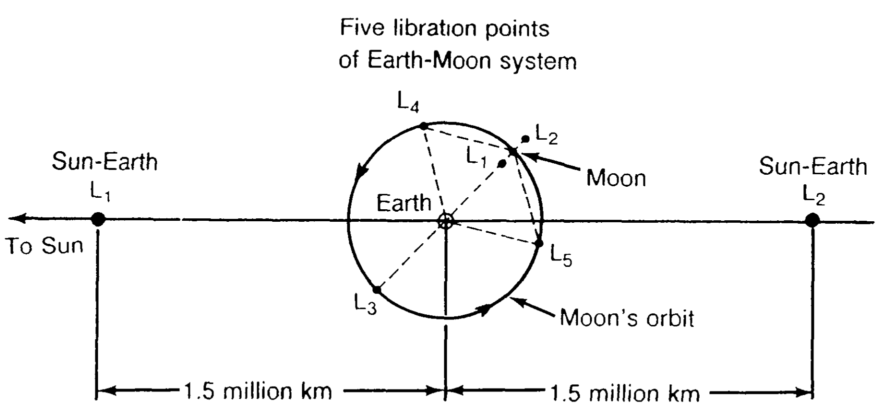


The justifications for such space activities are more than economic. They include

- Maintaining American security, leadership, and technological excellence

- The possible discovery of new resources, such as an ore body on the Moon or lunar polar ice, and of new uses for strategic areas, such as Lagrangian points (see box)

- Technology transfer to benefit global society, particularly the peoples of the Third World



Lagrangian Points

There are five positions of equilibrium in the gravitational field of an isolated two-body system. (The example shown fully in the figure is the Earth-Moon system; the L1 and L2 points of the Sun-Earth system are also shown; and a third example would be the Sun-Jupiter system.) As shown by the French mathematician Joseph Louis Lagrange in 1772, these "libration points" have the interesting property that, if a third, very small body were placed at one of them with the proper velocity, the centripetal acceleration of the third body would be perfectly balanced by the gravitational attractions of the two primary bodies. Three of the Lagrangian points are situated on a line joining the two attracting bodies, while the other two form equilateral triangles with these bodies.

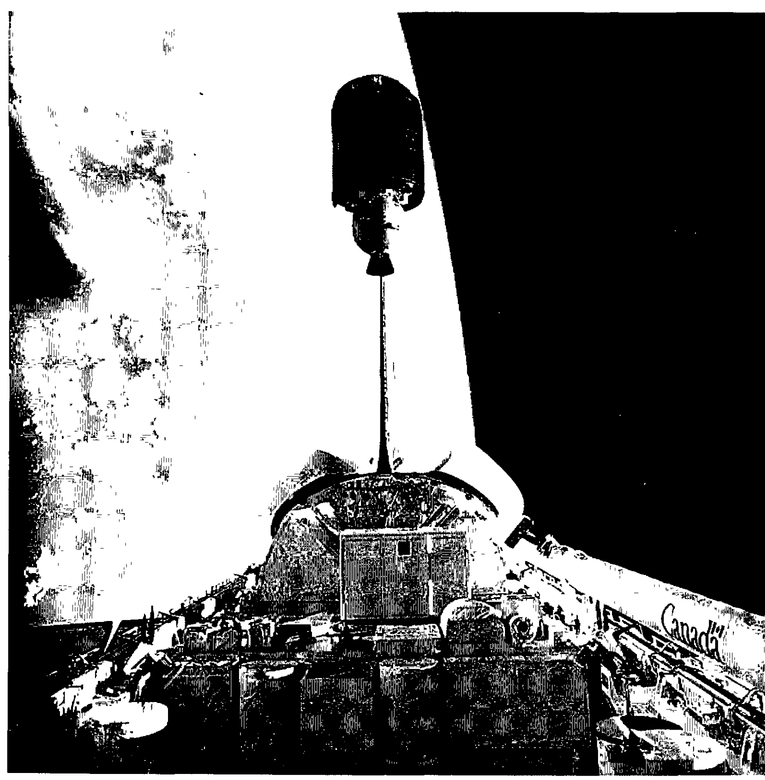
The so-called "Trojan asteroids" have been captured in the L4 and L5 points in the Sun-Jupiter system. The group of asteroids orbiting the Sun 60 degrees ahead of Jupiter have been named after Greek warriors (including Odysseus), and the group trailing Jupiter by 60 degrees have been named after warriors of Troy (including Aeneas). (Because of naming errors, there is at least one "spy" in each camp: Achilles' friend Patroclus is in the Trojan camp, and Hector, the greatest of the Trojan heroes, who killed Patroclus and was killed by Achilles, is in the Greek camp.)

This natural example and our understanding of the balance of forces at these locations lead us to consider the Lagrangian points as good places to put "stationary" satellites. Although the three collinear points are inherently unstable and the two triangular points are only quasi-stable, the station-keeping cost to maintain a spacecraft at or near one of these points for a long time is very small. A space station located at either L4 or L5 in the Earth-Moon system would require almost no fuel to keep it in place. And communication satellites located at L1 and L2 in the same system would require only small amounts of fuel for station-keeping.

Taken from Robert Farquhar and David Dunham. 1986. Libration-Point Staging Concepts for Earth-Mars Transportation, in vol. 1 of Manned Mars Missions Working Group Papers, NASA M002, June, pp 66-77

Economics and System Tradeoffs

The immediate rationale for extending human presence into space is primarily noneconomic—the human and scientific returns to be gained by such endeavors. Having said that, we recognize a viable market for the use of space in the communications industry. A case for investment in space industrialization has already been made by the success of commercial satellites and sensors. From parametric sensitivity analysis of the benefits vs. the costs of using space, it seems that information resources will have the most payback in the near term.



A Case for Investment in Space Industrialization

The Indonesian Palapa B communications satellite is just about to clear the vertical stabilizer of the Space Shuttle Challenger *as it moves toward its Earth-orbiting destination. The noneconomic benefits of such devices, making communication possible across undeveloped stretches of the Earth's surface, are readily apparent. So, too, are the economic benefits to the space industry which develops them. In the near term, such information resources will probably have the most payback. In the long term, the commercial prospects of energy and material resources may grow large.*

By the turn of the century, growth industries may emerge in space for materials processing, then eventually for manufacturing and mining, solar power, and other applications (see fig. 1). The Moon may prove to be economically attractive when production of oxygen, propellants, and bulk shielding materials is undertaken. The growth of human activities in space will continue to be limited by economic constraints, such as the high cost of transportation and of life support, both of which initially involve replenishment of supplies from Earth.

Since NASA is not an ordinary business but an R&D organization engaged in high-risk, high-technology, large-scale endeavors, the agency requires large amounts of up-front capital. Its financial requests should be evaluated by criteria that go beyond mere cost/benefit ratios. Although its ventures involve much risk, exposing national prestige as well as capital, NASA's space programs also require boldness because of the possible economic and other rewards to be gained by the country and the world.

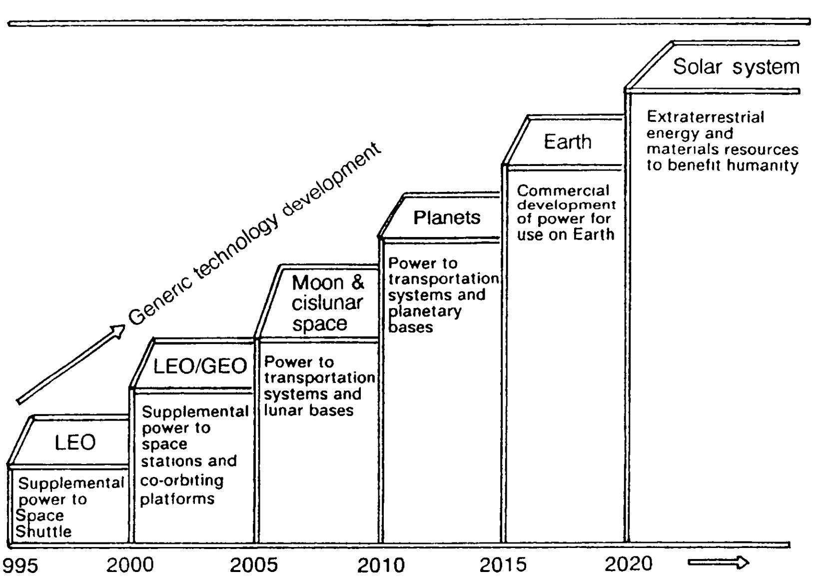


Figure 1

Growth Path for a Power Beaming Industry

Developing the capacity to beam power generated in space (from photovoltaic cells on an orbiting platform or at a lunar base) to other locations for use might become a growth industry. The power would first be beamed to space facilities only short distances from where it is generated. Later it might be beamed back to Earth or on to spacecraft moving farther out into the solar system.

Taken from Arthur D. Little, 1989, Report of NASA Lunar Energy Enterprise Case Study Task Force, NASA TM-101652, July, p. 82.

The principal system tradeoffs identified for the next 25 years are choices among (a) space transportation systems; (b) power systems in space and on the Moon; and (c) automation, human presence, or a combination of both. In attempting to develop cost projections for such purposes, NASA would be well advised to utilize new parametric models, such as the sensitivity analysis demonstrated in the 1984 summer study; it offers a method for testing and quantifying differing assumptions about space resources.

However, to create the necessary economic infrastructure for these space undertakings, new sources of income that go beyond the Federal budgeting of NASA requests are essential. New financial participation may come from tax incentives and other encouragements of space entrepreneurs and technological venturing. New legislation is desirable which facilitates space commerce and involves business on a broader basis than does the aerospace industry, while improving the insurance situation for space activities. Furthermore, new options should be carefully evaluated by the President and Congress for greater public financial participation in space endeavors that will spread the risks, such as through a national lottery, Government bonds, stock investments, or limited partnership opportunities. In such ways, the fifty existing space advocacy organizations might be mobilized, so that their collective membership of 300 000 and their aggregate annual budget of $30.5 million* would have greater impact on space development.

While NASA should be urged to pursue innovative ways to reduce the costs of its space transportation system and other operations, its budget should be increased to cover both operational commitments and new developments. Other financial benefits might come from developing technological systems that are more generic or building reservoirs of consumables onsite in space, using nonterrestrial materials when possible. Savings might be further effected by designing support systems that permit recycling and accept substitute sources or even substitute chemicals. Creative funding may involve the privatization of many space activities, so that the NASA budget can focus on research and development.

*M. A. Michaud, 1987, *Reaching for the High Frontier: The American Space Movement, 1972-84* (New York: Praeger).

Management and Structure

The next stage of space development poses a challenge for the management of large-scale technical enterprises, such as a space station and a lunar outpost. In this regard, we recommend that the nation's political leadership consider giving NASA a new charter—one that would allow it greater autonomy and flexibility (like the Tennessee Valley Authority). Perhaps all NASA's research functions should be concentrated into a National Institute of Space.

In this postindustrial information society, human systems like NASA are expected to go through a process of organizational renewal. Since NASA made management innovations during the Apollo period, it can capitalize on this heritage to meet the challenges of change in organizational culture and in the role of management, especially as a result of advances in management information systems (MIS). More behavioral science management research is also needed on (1) the role of, problems faced by, and skills required of space project leaders (both those who manage space resource undertakings from Earth and those who lead space programs onsite) and on (2) the macromanagement approaches required for effective administration of large-scale technological projects in space.

Legal, Political, Social, and Environmental Issues

Technological excellence in space will not only serve the needs of national pride, defense, and growth but also ensure America's leadership, especially in high technology and its applications. To energize the nation's will toward space development requires the creation of mechanisms such as the following, which we recommend to the nation's leaders for consideration:

- Foster a national consensus on our space goals by encouraging greater public involvement. The means might be a White House conference on space industrialization, town meetings or teleconferences, interagency forums on Government and military activities in space, a space congress of trade and professional associations on their roles in space, a convocation of space organizations and interest groups on NASA's needs and plans, space conferences for media representatives, a NASA summer study for artists and dramatists, and more educational programs on human migration into space. The International Space Year of 1992, the 500th anniversary of Columbus' landing in the Americas, might prove a suitable focus for such citizen participation in our country's space program.

- Foster the legislative environment and incentives that would encourage the private sector in space commercial enterprises. The means might be joint ventures with NASA, corporate consortia for space projects, Federal space insurance, and contracting outreach beyond the aerospace companies (e.g., into the robotics and automation and other high-technology industries).
- Foster international opportunities by NASA for joint endeavors with other national space agencies, both with allies and possibly with the U.S.S.R. The Apollo-Soyuz mission (see fig. 2) offers a precedent for creating peaceful space synergy. Much yet remains to be done in the utilization of space resources both for healthy competition and for international cooperation. Perhaps we should consider participating in an international mission to Mars.

Figure 2

Crewmembers of the Apollo-Soyuz Test Project Visit With President Gerald R. Ford

President Ford holds the Soyuz part of a model depicting the 1975 Apollo-Soyuz Test Project, an Earth orbital docking and rendezvous mission in which Americans and Soviets cooperated. With the President are Vladimir A. Shatalov, cosmonaut training chief; Valeriy N. Kubasov, flight engineer; Aleksey A. Leonov, crew commander; and Thomas P. Stafford, crew commander; Donald K. Slayton, docking module pilot; Vance D. Brand, command module pilot. Dr. George M. Low, NASA's Deputy Administrator, is behind President Ford.

Overall Desirabilities and Probabilities

Space is a place to motivate new modes of human cooperation. [The National Commission on Space (1986) offered specific recommendations in this regard.]

An imaginative plan for a lunar base might inspire the next generation to turn outward in pursuit of challenges on the next frontier. Space resources are vital for the development of human habitats and factories, be they on the Moon, on asteroids, or on Mars.

In the long run, human migration into space will not only alter our own human culture on Earth but also result in the creation of a new culture adapted to the realities to space living. Apollo 11 broke our perceptual blinders that we were Earthbound and opened up to us the possibilities for exploring and utilizing the universe. To prepare for the ever-expanding human presence in space, we need more study of

- Space ecological and life support systems by biochemists, microbiologists, research physicians, and other scientists. New policies will be needed on space ecology and the use of resources on the "high frontier."

- Design and construction at both the space station and a lunar base of a laboratory for the medical, chemical, biological, and psychological monitoring of the human inhabitants. A data bank could be developed for analysis of information on the human condition in long-term space living.

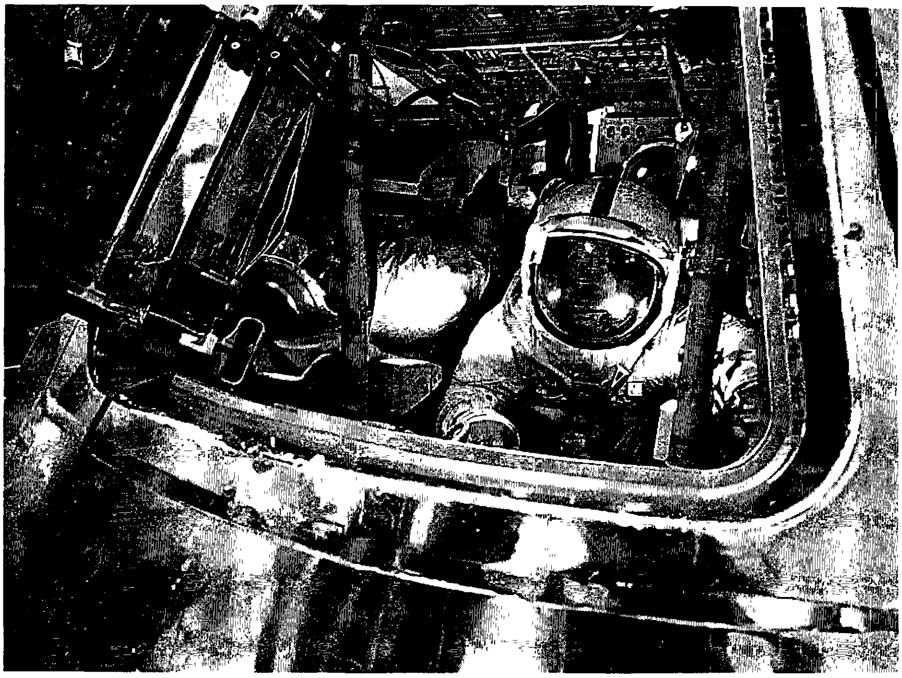
- Space ergonomics to obtain human-factor data and designs that will enhance the quality of life in a confined space environment and will reduce discomfort while people are engaged in space travel. Special attention should be directed to the human/machine interface and to the prolonged use of life support or safety systems.

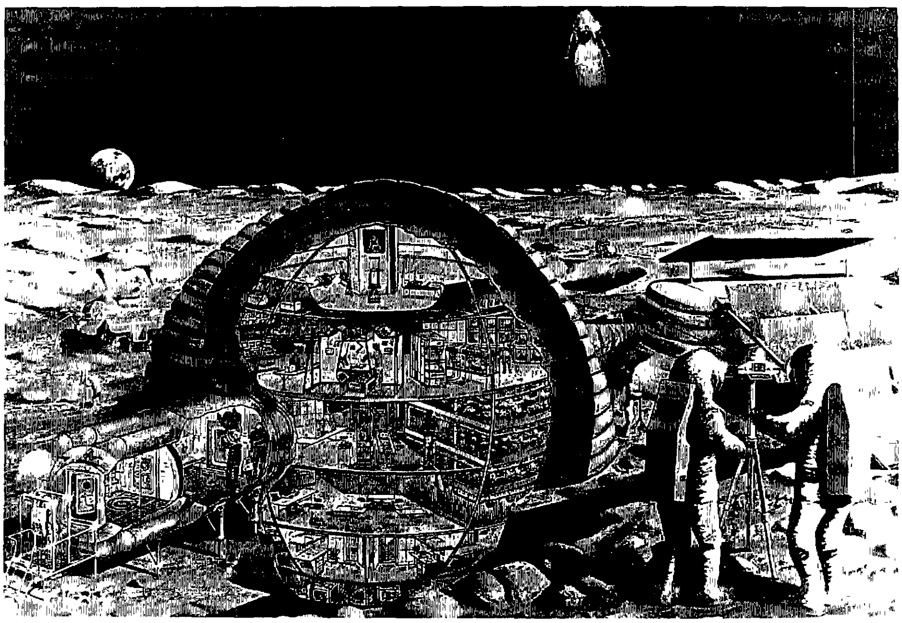
- Space habitat architecture that requires new concepts and materials. The latter will involve availability, end use, dual utilization, recycling, and substitutions. New processing techniques will be created that are suitable for the space environment.

- General living systems theory and planning that can contribute to the mapping out of human activities on the space station and on a lunar base, as well as provide continuous measures of major processes and energy flows.

The Crew Crowds Into the Command Module as They Simulate Their Apollo 16 Mission

The simulator shows how cramped the Apollo 16 crew must have been in their command module. Command module pilot Thomas K. Mattingly, II, faces the camera. John W. Young, mission commander, faces away. The helmet of lunar module pilot Charles M. Duke, Jr., can just be seen behind Mattingly's. Such tight constraints could only be endured on a relatively short mission. The Space Shuttle has provided a "shirt-sleeve" environment for astronauts to work in. For longer stays on Space Station Freedom, *at a lunar base, or on a mission to Mars, even more attention will have to be paid to the comfort of spacefarers*





Lunar Base Architecture

One concept for a habitat at a Moon base is this inflatable structure, protected from radiation by a continuous coiled bag containing lunar soil. Its construction crew lived in the simpler structure to the right, to which are attached a thermal radiator and solar power panels. The habitat, 16 meters in diameter, is designed to house 12 astronauts. It includes a gymnasium, which both makes use of the Moon's low gravity and counters its effects on the astronaut's physical condition; a control room; laboratories; a hydroponic garden, to provide fresh vegetables and to recycle exhaled carbon dioxide into inhalable oxygen; a wardroom for meals and meetings; and private compartments, located below the surface for extra radiation protection.

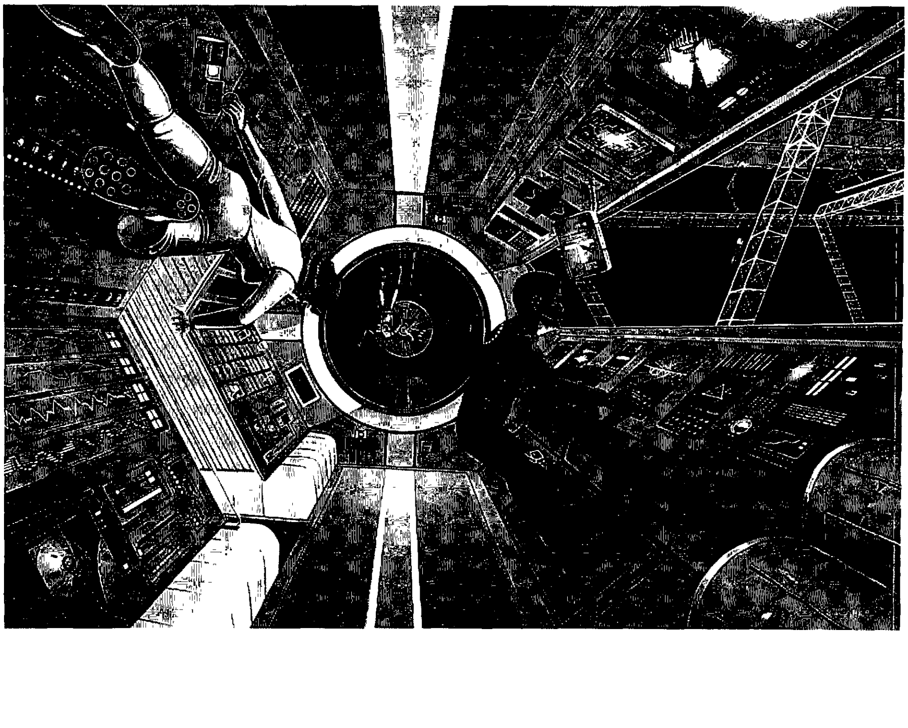
This painting shows a glove cabinet for handling lunar samples in a nitrogen atmosphere, as the Apollo samples have been handled on Earth for the past 20 years. With a permanent base on the Moon, such a substitute for the lunar environment would not be necessary. A more desirable procedure would be to take a small piece of a rock into the habitat atmosphere to study, throwing it away afterward, leaving the rest of the rock in place.

A problem not dealt with on the short Apollo missions but critical to a permanently inhabited lunar base is that of contamination by lunar dust. When the surveyors in the foreground return to the habitat, they will first pass through electrostatic wickets (seen on the left), which cause most of the dust to fall through the grate of this porch, they then remove their white coveralls, which protect the precision joints of the space suits from the gritty dust, and take an air shower in the dust lock; and finally they pass into the airlock to remove their suits.

These details show how a new environment requires innovative thinking.

The next 25 years offer lead time to plan for the more mature space communities to come. To cope with the unique conditions of life aloft, such as weightlessness and perpetual reliance on machinery, humans will adapt and acculturate, thus altering behavior. New living themes and patterns will change our sense of self, communication, dress, food, time, relationships, values, beliefs, mental processes, and work habits. To prepare for such revolutionary changes in the human condition, we need immediate research by cultural anthropologists and cross-cultural psychologists on such relocation issues as

- Crew selection and management for the space station and a lunar base. Increasingly heterogeneous and multicultural in composition, these crews will begin to stay in space for 180 days or more. Matters of personnel rotation, interpersonal and group dynamics, leadership and team building, in addition to the use of local space resources, demand more study now if such people are to work together efficiently, safely, and congenially.



An Early Concept of Life Onboard a Space Station in Low Earth Orbit

The selection and management of the increasingly heterogeneous crews who will live together under the stressful conditions of a space station or a planetary base are matters that demand more study now to ensure that such people will work together safely, efficiently, and congenially.

Artist: Jerry Elmore

- Space personnel deployment systems that would provide a comprehensive acculturation program for life in space. Such a system might entail (a) recruitment and assessment, (b) orientation and training before departure, (c) onsite support and monitoring, and (d) reintegration upon return to Earth.

Conclusions

The increased number and diversity of people going into space beginning in the next 25 years requires research and development into more areas than just transportation, energy, and materials. It necessitates expansion of studies in the human sciences on issues of life support, safety, ergonomics, habitats, communities, and relocation of people, as well as the ecology of space resources. The situation would seem to warrant a more comprehensive, systematic approach to such planning.

The human race is in transition from an Earth-based to a space-based culture. Although this "passover" may take centuries, we are now taking the first revolutionary steps toward the time when we can regularly, economically, and safely extend out from low Earth orbit to the orbit of the Moon. Perhaps there we humans will really mature and achieve potential as we move out into the universe and a new state of being.

NASA in the 21st Century: A Vision of Greatness

Kathleen J. Murphy

Abstract

We in the United States face an awesome challenge: NASA's role well into the next millennium must be decided *now*. The project goals to be achieved over the next quarter century need to be set in order *now*. Our scarce financial resources need to be allocated *now* to those projects that will maximize our long-term productivity.

NASA's course must be worthy, its execution impeccable, and its understanding of (and tolerance for) risk tailored to the unique developmental requirements of each situation.

- **Defining a worthy vision for the NASA organization**

  The first section of this paper discusses notions of greatness that have guided NASA in the past, presents values that might be delivered by NASA in the future, and examines the skills required for NASA to execute a vision of greatness.

- **Scoping a strategically significant mission agenda**

  The second section reviews three possible patterns of space development by NASA: (1) a mission to protect the ecology of the Earth, (2) the engineering of the technologies critical to space transportation and a healthy, productive life in space, and (3) the management of a major nonterrestrial resource project.

- **Sourcing—and sustaining—optimum financing**

  The paper's third section discusses potential sources of funds, opportunities for sustainable collaboration, and the life cycle of NASA's funding responsibility for its space development program.

Alternatives are abundant. The key to success, however, is our willingness as a nation to commit to a shared notion of greatness. Only steeled by such a commitment can we hope to make the wealth-creating technological advances and significant scientific discoveries to sustain our leadership into the 21st century.

A lot has happened since the 1984 NASA summer study, and even since the 1989 declaration by President Bush—on the occasion of the 20th anniversary of the landing on the Moon—that the U.S. space program will be redirected toward sustained exploration of space. Who would have imagined that in this short time peace would break out all over: that urgent longings for democracy would thrust China into a massive internal rebellion; that the yearnings of Eastern Europeans would thrash the Berlin Wall to dust; that in the space of a few weeks skeptical Romanian and Czechoslovakian people would shake off their totalitarian systems in completely decent and peaceful ways. The surprising occurrence of these monumental events fills one with awe and wonder at the changes that lie ahead as we near the end of a millennium. One can only imagine the truths we have yet to discover, the many realities yet to unfold.

Full of hopes, dreams, visions of where these blossomings may lead us as a global community, we are at the same time crushed by alarming realities at home—weighed down by our massive budget deficit, surprised at the growing political irrelevance and eroding commercial competitiveness of the United States in the world, and shattered and saddened by the problems plaguing the former hallmark of our technological prowess, the National Aeronautics and Space Administration, in the aftershock from the Space Shuttle *Challenger* disaster—the January 1986 explosion that thrust the organization into a massive reevaluation. And now an agenda is under consideration that is so broad, so costly, and so far beyond the scope of human experience to date that the risks are extraordinary. It is only with courage and humility that cost estimates of these yet uncharted courses can even be attempted, as the potential for unpredicted events is enormous.

In November 1989, NASA laid out five approaches to going to the Moon and Mars using techniques and technologies the agency had studied for years and sometimes decades. Implementation would take more than a quarter of a century at a cost of $400 billion. That is regarded by the current Administration as simply too long and too much (Hilts 1990b). Eager to arrive at a realizable agenda, the Bush Administration has commissioned exhaustive brainstorming to refocus and redirect the U.S. space program, under the guidance of the National Space Council and its head, Vice President Dan Quayle. How can the "Bush vision" be molded into a challenging, yet realizable, program supported by adequate, consistent funding? How can NASA best prepare itself to bring the Bush Administration's redirection to fruition? This paper assesses NASA from organizational, strategic, and financial perspectives to determine if it is well positioned to meet the challenges of space exploration and development on into the next millennium:

- Defining a worthy vision for the NASA organization
- Scoping a strategically significant mission agenda
- Sourcing—and sustaining—optimum financing

Section 1: Defining a Worthy Vision

Leaders, through their visionary grasp of the possible, energize their followers and marshal them toward fulfillment of the goal. A vision is an energizing view of the future role or function of an organization, including its distinctive values, skills, and operating style. As a coherent directive, a vision statement provides focus: it provides a context for evaluating the appropriateness of potential missions and objectives; it suggests criteria for distinctive performance; and it empowers decision-makers throughout the organization to raise issues, assess options, and make choices. Always articulating the value to be delivered to those having a stake in an organization, the vision statement further provides a standard against which to evaluate external competitive positioning of the organization over the long term.

The Bush Administration perceives that there is a crisis of vision. Vice President Dan Quayle has commented that "Despite our continued scientific and technological preeminence, our Government has not done as well as it could have in marshaling the resources and the leadership necessary to keep us ahead in space. Our competitive advantage in technology has disappeared" (Hilts 1990b). Such a perceived crisis of direction cannot be tolerated for long, because NASA, our spearhead of technological innovation, has a responsibility of critical strategic significance to our nation. To ensure that NASA is on a worthy course, a vision of NASA's future greatness must be clearly defined, the value to be delivered by NASA must be fully understood, and the skills and style required to execute the vision must be specifically identified.

Notions of Greatness

The directive to explore and develop space is a boundless undertaking that is not likely to reach fruition in our lifetime (unless, of course, our technological breakthroughs advance at an exponential rate, or unless we have the good fortune to come to know other intelligence in the universe that has already figured everything out).

In contrast, the U.S. space program appears to have undergone short-term eras of leadership, demarcated by changes in President. The U.S. space program, framed by the President's vision perhaps more than any other program because of its discretionary financing, is often planned in terms of accomplishments realizable during that President's term in office. The implemented program is the result of an iterative process: The vision set by the President is constrained by the financial resources allocated by Congress, delimited by the technological capabilities held in hand by NASA (and other U.S. academic, commercial, and engineering institutions), and dependent on the willingness of the American people to sustain support over the project lifetime. There is an expense involved in this iterative process: Each change of vision creates new issues, alters priorities, and redefines standards. It is far more cost-effective to develop a strategy for human exploration of the solar system that can endure for at least 20 years, longer than the term of any one President, most members of Congress, or the average NASA manager (Aaron et al. 1989).

NASA has had at least three distinct directives since its inception in the 1960s, not counting the redirection under way since the Bush Administration took office (see table 1). A brief review of these "strategic eras" demonstrates the impact of Presidential vision on the organization up to now and suggests parameters for the most effective vision statement for the 1990s and beyond.

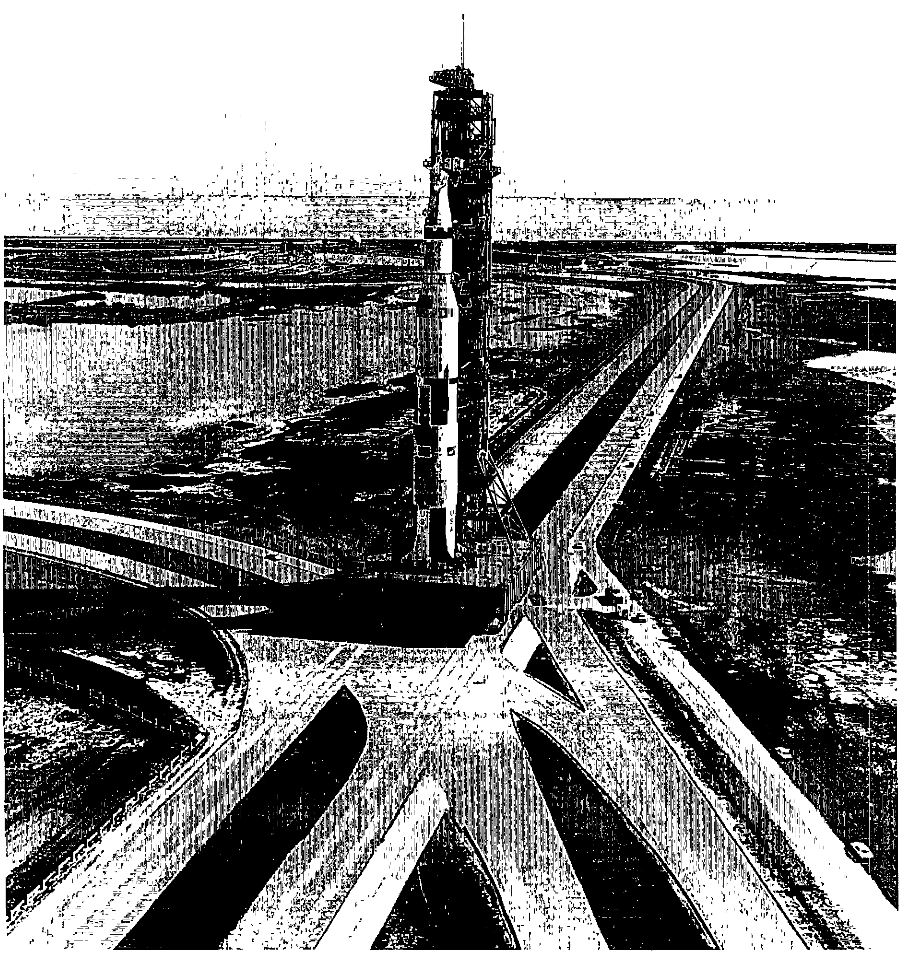
The Kennedy Vision: Establish U.S. technological supremacy in the world.

President John F. Kennedy launched the space program with a bold vision and a determined foresight that have not been enjoyed since. Envisioning the U.S. space program as the establisher of U.S. technological supremacy in the world, he chose as the focused mission objective a race to place a man on the Moon and return him safely to the Earth before the end of the decade. The entire program was a masterful demonstration of management efficiency and control, as the mission, relying on hundreds of thousands of subcontractors, was completed on time and on budget. The Apollo Program achieved the desired technology goals, as it reawakened interest in science and engineering, enhanced international competitiveness, preserved high-technology industrial skills, and marshaled major advances in computers and micro-miniaturization (Sawyer 1989). The program was awe-inspiring, enjoyed enormous funding support, and established a reputation for NASA that was to endure until it blew up with the Space Shuttle *Challenger* in January 1986.

TABLE 1. *The U.S. Manned Space Program, 1960-2000: Strategic Eras and Program Effectiveness*

Characteristics	1960s Kennedy Initiative	1970s Nixon Compromise	1980s Reagan Commercialization	1990s Bush Redirection
Vision	Establish U.S. technological supremacy	Provide economical access to space for military & commercial purposes	Foster a private-sector space industry	Establish U.S. as preeminent spacefaring nation
Mission	Place a man on the Moon & return him safely to the Earth	Create a reusable transport vehicle: capture 75% of commercial payloads worldwide	Build a space station to develop commercial products	Establish a permanent entity in space; begin sustained manned exploration of solar system
Budget	$ billion/yr 3.25 (26/8)	$ billion/yr 3.0 as of '74	$ billion/yr 7.5	$ billion/yr 13 est. (400/30)
Performance	On time, on budget (one-time event)	Late, over budget (missed economic objective)	Late, over budget, redefined several times, uncertain	Taking a fresh new look
NASA management	Masterful	Ineffective	Confused	Potential resurgence
NASA bargaining leverage	Strong: generous support & funding	Moderate: constant renegotiation to increase funding	Weak: constant budget-cutting & rescoping	Potential improvement
Public esteem	High, inspired	Neutral	Seriously eroded	Potential renaissance

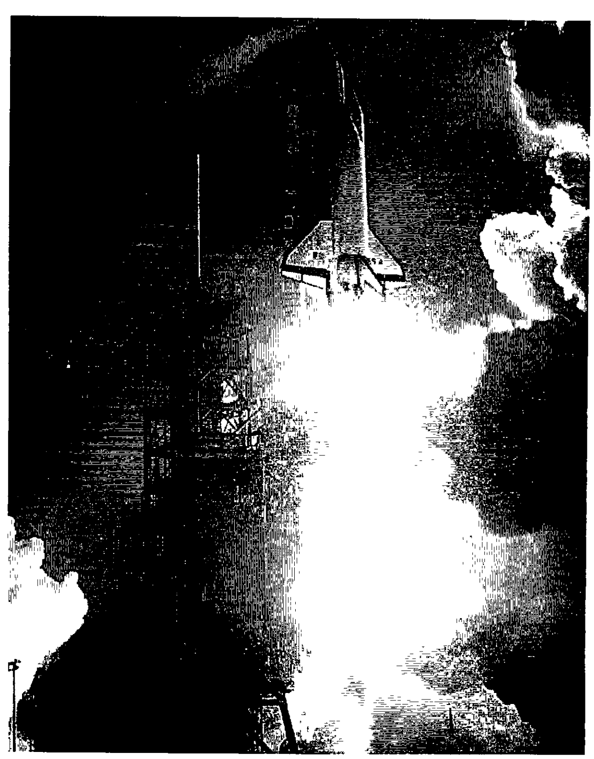
Sources. Banks 1988, Chandler 1989, Chandler and Mashek 1989, Sawyer 1989, Steacy 1989



Apollo 14 Rollout, Nov. 9, 1970

The Nixon Vision: Provide economical access to space for military and commercial purposes.

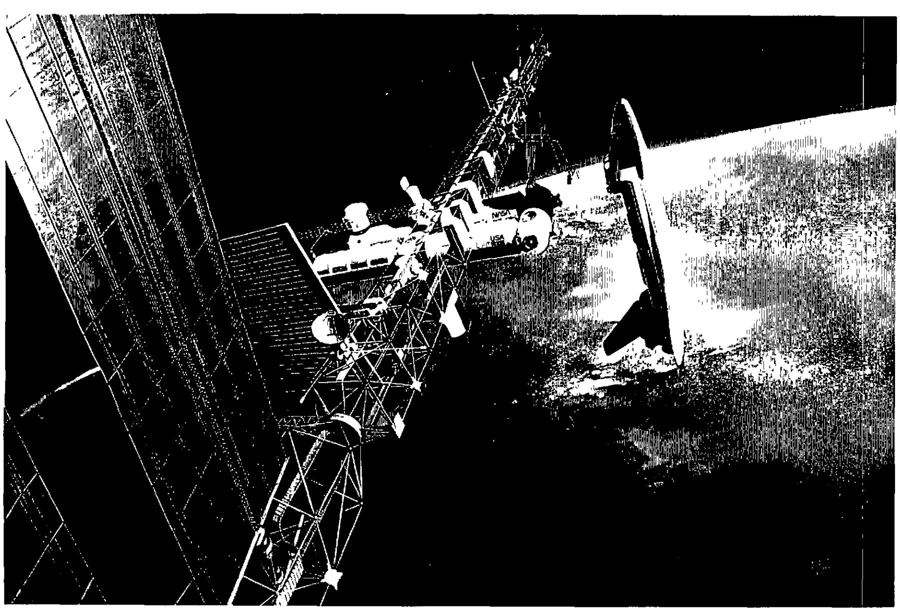
President Richard M. Nixon chose a very specific vision which, if successful, would have provided important commercial benefits to the United States and, if realized during his term of office, would have been a credit to his administration. He envisioned NASA as providing economical access to space for military as well as commercial purposes. The mission, which was specifically articulated, was to create a reusable transport vehicle that could capture 75 percent of the commercial payloads worldwide. While a reusable Space Shuttle has been developed and put into operation, it has never achieved the economic objectives which were an essential component of the vision. The Shuttle will simply never be able to provide the cheap, versatile, and reliable access to space it was supposed to, because it is a complex and sophisticated vehicle—a Ferrari, not a truck (Budiansky 1987-88). Nevertheless, the National Academy of Sciences has noted that the Space Shuttle engine was the only significant development in space propulsion technology in the past 20 years.



Lift-Off of STS-1, April 12, 1981

The Reagan Vision: Foster a private-sector space industry.

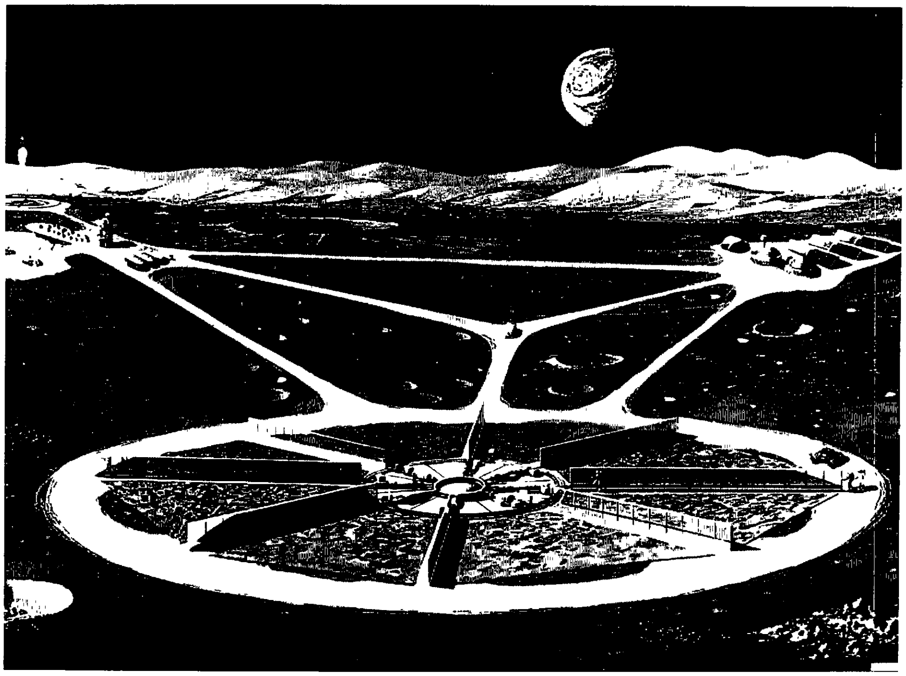
The directive to establish a permanently manned space station was a subsidiary mission in the Reagan era, subordinate to his vision of a Strategic Defense Initiative (SDI). However, to be worth $30 billion, the space station should really serve some worthwhile national purpose. Commercial applications have obviously been grossly overstated, As companies have backed off space manufacturing since solutions have already been developed on Earth. Furthermore, such a mission had been rejected in favor of the lunar mission by President Kennedy in 1961, a space station not being considered bold enough for the 1960s (Del Guidice 1989) (although Skylab was built, flown, and manned three times in the 1970s).



***Concept of Space Station* Freedom**
Artist: Al Chinchar

The Bush Vision: Establish the United States as the preeminent spacefaring nation.

President George H. W. Bush's tentative vision for the U.S. space program is of "spacefarer," suggesting a navigator, one who sets or charts a course. His priority missions are to establish a permanent entity in space and begin sustained manned exploration of the solar system. At this writing, the mission agenda of the Bush Administration has not been finalized. Vice President Quayle has requested that the NASA Administrator, Richard H. Truly, ensure that our space exploration program is benefiting from a broad range of ideas about different architectures, new system concepts, and promising technologies, as well as opportunities to cut costs through expanding international cooperation. He asked Truly to query the best and most innovative minds in the country—in universities, at Federal research centers, within our aerospace industry, and elsewhere. NASA will take the lead in the search and will be responsible for evaluating ideas (Broad 1990a).



Concept of a Lunar Base, Featuring the Radiator of Its Nuclear Power Plant

Alternate: The Havel Vision: Uncover the secrets of the universe.

In a 1990 interview,* Vaclav Havel, President of the Czechoslovak Socialist Republic, stated that we still have a long way to go in our development, as we still have not yet "uncovered the secrets of the universe." It is interesting to select such an idea as an alternate vision, as a "control" to assess whether President Bush's notion of greatness goes far enough and is sustainable over the long term. Effectively, the difference between "spacefaring" and "secret uncovering" is that between the means and the end, the journey and the arrival.

Vaclav Havel, a former political prisoner and a playwright, has demonstrated a clarity and a profundity in his political statements at Czechoslovakia's helm that are truly visionary and thought-provoking. On the occasion of his visit to the U.S. Congress in February 1990, he articulated the pace of change: "The human face of the world is changing so rapidly that none of the familiar political speedometers are adequate. We playwrights, who have to cram a whole human life or an entire historical era into a two-hour play, can scarcely understand this rapidity ourselves." And he articulated his vision of the role of intellectuals in shaping the new Europe—which can be compared to the role of space technology and science in clearing the path for the space age: "The salvation of this human world lies nowhere else than in the human heart, in the human power to reflect, in human meekness, and in human responsibility. The only genuine backbone of our actions—if they are to be moral—is responsibility. Responsibility to something higher than my family, my country, my firm, my success" (quoted by Friedman 1990).

Recognizing that everything we know of any importance about the universe we've found out in the last 50 years or so (Wilford 1990a), it would not be unrealistic to expect great truths to be unfolded in the 50 years to come. Numerous projects on NASA's drawing boards today promise to unlock important secrets in the near future. For example, it is hard to imagine a more exciting secret than whether or not there is other intelligent life in the universe. The Search for Extraterrestrial Intelligence (SETI), a proposed $100 million, 10-year project, funded by NASA but operated by an independent nonprofit group, plans to build a highly advanced radio receiver that will simultaneously scan 14 million channels of radio waves from

*With Barbara Walters on the ABC television program *20/20*.

existing radio telescopes around the world. The National Academy of Sciences has stated that it is hard to imagine a discovery that would have greater impact on human perceptions than the detection of extraterrestrial intelligence (Broad 1990b).

Expected Values

The vision statement conveys standards of excellence: "Be a technology leader." "Provide transportation economically." "Be an explorer, a navigator, a spacefarer." It determines which values are given precedence, thus providing a standard by which to determine relative degrees of excellence, usefulness, or worth of tasks performed within the organization. Each value to be delivered targets a potential competitive advantage or some economic leverage to be derived from realization of the vision. The purpose of a commercial organization is to create wealth for its shareholders. As a Government-sponsored institution, NASA has a value to its shareholders—the U.S. taxpayers—that is much broader and more complex.

A review of the literature reveals a broad range of opinions held by the public regarding what NASA's value is. Probably the lively debate over the efficacy of the space program exists precisely because of this wide disagreement. The composite list of "values" that NASA "should" be delivering, which follows, seems remarkably similar to Maslow's hierarchy of needs (fig. 3), from the most basic physiological need for survival (deriving economic "bread" from commercial activities), through safety, social, and esteem needs, and finally to the peak experience of creativity and self-actualization. Maslow's theory postulates that the most basic needs must be satisfied before higher needs can be addressed.

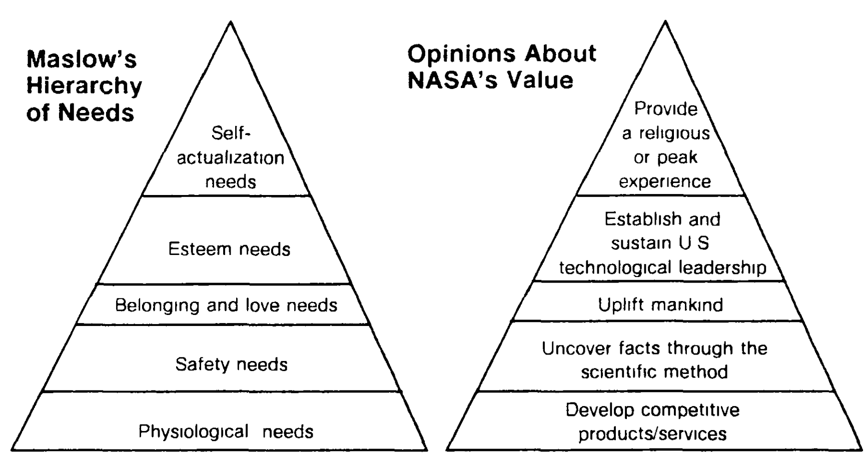


Figure 3

Maslow's Hierarchy of Needs and Opinions About NASA's Value

A leader of the humanistic psychology movement, Abraham Maslow was concerned primarily with the fullest development of human potential; thus, his burning interest was the study of superior people. His theory of human personality has become probably the most influential conceptual basis for employee motivation to be found in modern industry. The needs occur in the order in which they are presented, physiological first. Until one level of need is fairly well satisfied, the next higher need does not even emerge. Once a particular set of needs is fulfilled, it no longer motivates.

Source: Rush 1976.

Develop products and services with clear economic advantages.

Many look to NASA as a wellspring of new product and service innovations that are expected to keep the U.S. economy competitive in the world. This economic focus expects a perfectly managed program (on the order of the Apollo days) with only outstanding economic results. Any news about the difficulties of engineering the highly complex technologies of today is not welcome. NASA is given causal responsibility for ensuring U.S. competitiveness in the world: "Space leadership and technological leadership are tied together. Just as technological leadership and American competitiveness are tied together" (Anderson 1988). Furthermore, NASA is expected to fuel as well as fully interact with the private sector in their joint development and spinoff efforts. "In the vastness of technology, mutual dependence between government and the private sector nourishes both"—Thomas G. Pownall, Chairman, Martin Marietta (Rappleye 1986).

Uncover facts through the scientific method.

Others see NASA as a herald of science: both putting scientific knowledge to work in the engineering feats of space exploration and adding to our scientific understanding of the solar system. This view suggests an approach to space exploration that minimizes threats of loss of life or health, a highly disciplined approach grounded in the scientific method. Indeed, with the exception of the race to put the first man on the Moon, NASA has approached solar system exploration in a step-by-step fashion. And remarkable engineering and scientific accomplishments have been made by NASA's missions to the Moon (Ranger, Surveyor, Apollo) and to the planets (Mariner, Pioneer, Viking, Voyager). Scientist astronaut Sally Ride thinks NASA should continue in this tradition. She has stated that NASA should avoid a spectacular "race to Mars" and establish a lunar outpost as part of a measured exploration of the solar system. "We should adopt a strategy to continue an orderly expansion outward from the Earth . . . a strategy of evolution and natural progression" (quoted by Broad 1989). Other space experts would like NASA's scientific focus to be inward toward the Earth. "We'd better pursue the things that work in space, like surveying the Earth's resources, weather patterns, climatic change—things of direct and daily human importance" (Brown 1989).

Uplift mankind.

There are more emotionally motivated constituents who value NASA not for what it does scientifically but for the social, cultural, or political impact it has on our collective consciousness, whether national or global. The success of the space program as "a cultural evolution may open many new options, including opportunities to ease global tensions, help the developing world, and create a new culture off our planet" (Lawler 1985). "The U.S. will again lead the world in developing space for the benefit of its citizens and future generations throughout the world" (Rockwell 1986). "Going to Mars is an international endeavor. Political benefits can be derived immediately—not 30 years from now but every year, through a joint project with other countries, and the Soviet Union in particular" (Del Guidice 1989). Perhaps the most shining example of this ability of the space program to uplift and unite is the phenomenon of more than 600 million people who gathered at their local television sets around the world in July 1969 to witness the U.S. landing on the Moon 241 500 miles away.

Establish and sustain U.S. technological leadership.

Others view NASA as the determinant of our technological leadership in the world and therefore a source of esteem. "It is humanity's destiny to strive, to seek, to find . . . it is America's destiny to lead" (Rosenthal 1989). Essentially, "we must either reaffirm U.S. preeminence in space or permit other nations to catch up or surpass us at the crucial juncture" (Gorton 1986). Under this value system, leadership can be dangerously misconstrued to mean "pay for everything." True opportunities for differentiated, competitive leadership need to be understood and aggressively pursued; however, the basis of world esteem for our space program should be authentic technological achievement and not simply financial daring.

Provide a religious or peak experience.

Finally, there is a profoundly fulfilling dimension to truly marvelous achievements and truly humbling failures. "There is something almost religious about man in space. The human exploration of the solar system appears quasi-religious, while automated exploration is 'pure science'" (Brown 1989).

Space exploration has a profound moral dimension that cannot be transgressed. The natural law, when followed, leads on to fulfillment of the mission but, when violated, leads to difficulties and even death. In these days of avarice and deception that seem to escape the heavy hand of justice, the joys and sorrows of space exploration are tied to a morality that does not play favorites. Compare the infamous Wall Street "junk bond" crisis or the savings and loan debacle, engineered by those who made their own rules and used the system for personal gain, violating all standards of fair play, to space explorers, who are obliged to uncover "the" rule and advance strictly within its limits. In spite of the wonderful heroism of the seven astronauts who rode the *Challenger* to its demise, the violation of the temperature limits of the "O" rings led to immediate ruin. It is the very discovery of the rule—how things work—that makes the quantum leap possible. Effective communication of this "truth" and "honor" of technological and scientific exploration is sure to shift prestige away from Wall Street and draw career candidates into engineering and science.

Space exploration will entail extraordinary adventure and discovery, but also enormous risk and personal sacrifice. The deep personal commitment that will be required to depart on the long journey replicates the religious motif of death and resurrection:

> I shall stretch out my hand unhesitatingly towards the fiery bread. . . . To take it is . . . to surrender myself to forces which will tear me away painfully from myself in order to drive me into danger, into laborious undertakings, into a constant renewal of ideas, into an austere detachment. (de Chardin 1972, p. 23)

One might wonder how a Government-sponsored research agency could possibly fulfill this broad range of expectations. In fact, excellent performance of the task which NASA does best—advancing technology and science—will provide both practical and ennobling results.

> . . . if some observer were to come to us from one of the stars what would he chiefly notice?
>
> Without question, two major phenomena:
>
> the first, that in the course of half a century, technology has advanced with incredible rapidity, an advance not just of scattered, localized technical developments but of a real *geotechnology* which spreads out the close-woven network of its interdependent enterprises over the totality of the earth; the second, that in the same period, at the same pace and on the same scale of planetary cooperation and achievement *science* has transformed in every direction—from the infinitesimal to the immense and to the immensely complex—our common vision of the world and our common power of action. (de Chardin 1972, p. 119)

It is the almost instantaneous globalization of technological innovations and the transformative impact on quality of life of scientific breakthroughs that contributes, day by day, to the emergence of a vision of one citizenry, one planet.

If this set of expected values is held up to the Bush and Havel visions, we see that the Bush vision may influence technology development and require the advancement of science to steer the course; the Bush journey may establish our leadership position—if we are the first to make it; the journey may require courage and thus be inspiring. But Bush's vision does not have the closure that Havel's vision has. If we make the journey in order to uncover the secrets of the universe and if we succeed in realizing that vision, it is certain that a peak experience filled with awe and wonder will be an integral part of "truth's" unfolding.

Elements of Excellent Execution

A worthy vision, excellently executed, reaps outstanding results. Skills form the bridge between strategy and execution. The expected values determine the kind of skills needed. American taxpayers look to their national space exploration and development program for highly competitive new products and services, scientific facts, an uplifting perspective, preeminent technological leadership, and ethical and moral fortitude.

Excellence, grace, skill in execution conveys an organization's essence or style. But NASA does many things. NASA is not a single business unit, but a broad, rich organization with activities under way on many levels. What does NASA do? NASA is a problem-solver, trying to diagnose the startling environmental symptoms occurring on Planet Earth; NASA is an innovative engineer of technological advances; NASA is a conceiver, designer, implementer of "big science" experiments and exploration projects; NASA is the developer of the Space Shuttle and Space Station *Freedom* and would like to be the developer of colonies on the Moon and Mars; and NASA is the operator of the Space Shuttle, although operations are clearly not within its charter. Each set of functional tasks requires a different set of skills and styles of management as well as distinctive guidelines and criteria for measuring results and assessing whether they are appropriately aligned with the overall vision. It is the vision, however, that pulls all of these incongruous tasks together and weaves their diverse contributions into a single recognizable achievement.

However, the vision must be decided upon: Which vision, "spacefarer" or "secret uncoverer," best focuses the NASA organization on worthy accomplishments over the next 20 to 30 years? My purpose here is not to promote one visionary concept over another but rather to demonstrate the role and function of a vision in coloring the entire decision-making process within an organization.

The Skilled Professional

Excellent performance of NASA's multitude of tasks requires a rich array of the very best skills available in America today. Nothing less than the very best minds should be brought to bear on this major potential to revitalize our nation. The critical skills essential to executing NASA's numerous tasks include

- Visionary leadership
- Technical competence
- Entrepreneurial judgment
- Problem-solving ability
- Project management expertise
- The ability to innovate/experiment/create
- Navigational skills

The notion of vision ranks these critical skills and determines who will implement the vision. If we want to be the preeminent spacefarers, then perhaps navigational skills and entrepreneurial judgment will be the critical skills required by the organization. However, if the pursuit is of truths about the universe, then perhaps the ability to solve problems and the ability to innovate, experiment, create will be the most critical skills required.

The skilled professional may be homegrown or hired with the appropriate experience or contracted to fill a short-term need. But we will apply different evaluation criteria in searching for a "spacefarer" than in searching for a "secret uncoverer." To realize the "spacefarer" vision, we would look for the characteristics of an explorer, an adventurer, a risk-taker. To accomplish the "secret uncoverer" vision, we would need a more rigorous expertise based on proven results in innovating, discovering, inventing. The first suggests a fortitude in facing the unknown. The second suggests facing the unknown, wrestling the unknown to the ground, and rising victorious with insight into its parts and how the parts relate to each other to create the whole. The criteria for selection become more rigorous; the measures of successful performance, more precise.

The only way to reduce the timeframe and cost of research and experimentation and maximize effectiveness is to bring the best minds to bear on critical problems. Even if a premium must be paid over industry rates to attract such talent, the resulting maximization of NASA's output with respect to its vision would more than compensate for the increased investment in human capital.

To be able to respond agilely to problems and projects as they arise, NASA should be exempt from certain Civil Service regulations and be given flexibility in personnel hiring, advancement, retirement, and the assembling and disbanding of teams, as well as the resources to reward truly significant, ground-breaking, wealth-creating contributions.

The Pivotal Job

The pivotal jobs are those that are critical to demonstrating the vision. Those holding such jobs are effectively the delegated vision actualizers who, given sufficient leeway, exercise their judgment, intuition, and responsibility in service of the vision.

Jobs are considered pivotal if they are essential to convincing the American taxpayer that NASA is producing the desired result or achieving the desired strategic objective. They demonstrate that the vision is becoming actualized. Pivotal jobs might include

- The visionary leader, who can see, smell, taste, feel the fruition of the project
- The engineer, who ushers in technological breakthroughs
- The entrepreneur, who spins them off
- The scientist, who methodically unfolds discoveries
- The project manager, who shepherds the contributions of thousands of specialists within the "real-world" parameters of schedule and budget
- The communicator or brainstormer, who constantly stirs up, tears apart, refreshes, revitalizes the organization
- The astronaut, who navigates the spacecraft, who braves the unknown, and who will explore, develop, and inhabit space beyond our Planet Earth

If we are to be a nation of spacefarers, it is the astronaut who holds the pivotal job of demonstrating to the American people that we are indeed venturing out into space, navigating beyond Planet Earth. However, if we are to uncover the secrets of the universe, the engineer, the scientist, the brainstormer or communicator might hold the pivotal job, as such tasks embody the exhaustive search for unnoticed relationships and their significance.

The Focused Team

The projects on NASA's drawing board are beyond the ability of any single organization to implement, let alone single individuals. So, although it is critical that each individual represent the very best human potential our country has to offer, each must also have the uncanny ability to enrich, nourish, and apply that expertise in pursuit of a common goal, through highly focused teamwork. The end-product parameters must be clearly defined, and the accumulating insight must be continously shared among team members.

An individual professional's skill permits ready execution of a task at a high level of competence. An issue of concern is the potential dichotomy between the highly specialized professional and the highly synergistic team. Each specialist has his own vision of quality achievement and his own sphere of personal interests. Only through an over-articulated, single noble vision can sufficient energy be unleashed to inspire all toward a common goal. Such approaches as establishing broad spheres of responsibility, using teams extensively, and searching for job rotation opportunities continuously can nourish an ability to see connections and implications and foster more efficient, decentralized decision-making.

As an example, Ingersoll-Rand collapsed the design cycle of a new handtool to 1 year—one-third the normal development time—by breaking down the barriers within the entrepreneurial team and allowing sales, marketing, engineering, and manufacturing to work in unison; i.e., getting everyone to "play in the same sandbox." To avoid the "not-invented-here" syndrome, a core team representing all functional areas held weekly meetings to ensure that, among other things, all members had a stake in every step and it was a team project (Kleinfield 1990).

Staying centered on the creative process and remaining always fresh and innovative requires the ability to focus. The Bureau d'Economie Theorique et Appliquee (BETA) research group believes that innovation is, above all, a process. BETA has conducted four large research programs in the past 10 years, including a study of the space program to illustrate technological learning or change within an industrial network. They have concluded that innovation is an evolutionary phenomenon rather than a sudden happening (Zuscovitch, Heraud, and Cohendet 1988).

A compromising environment may get the journey under way, but it will not lead to the fullness of "truth." Such pressures as scoring achievements within a term-in-office timeframe; restricting a project to certain cost limits dictated by the national debt; establishing premature international collaboration simply because we are broke; sticking to known and established technologies no matter how inapplicable they may be; readily accepting unproven technologies because they're supposed to be cheaper—all these pressures constrain the investigative process and lead to half-baked results. If we are going to conduct an exploration program, we should provide the time and money to do the job right.

Where does one begin? How to achieve change, how to start the change process, how to assess whether members of the organization are prepared for change, how to handle obstacles to progress—these are all issues of concern, yet they are all surmountable. The important point to keep in mind is that organizations change all the time. Change readiness can be assessed at all levels of the organization, jobs can be redesigned, skills can be built, and any vision, eagerly embraced, can be brought to fruition.

The Coordination of Complexity

The most significant feature of the NASA space program, as compared to all the other programs on Earth today, is the enormous complexity of each individual project and the cumulative complexity of the program in its entirety. The simple experience of engaging our minds in the mastery of such mega-scale products, processes, and projects creates an expertise that serves us well in all aspects of our economic endeavors and in our global competitive positioning. In other words, this managerial experience—in itself—provides a unique competitive advantage to our nation.

The Brilliant Achievement

What makes an achievement stand out in our mind as brilliant is colored by our vision. The Apollo landing on the Moon is an example of an impeccable journey. The project was perfectly timed, sequenced, and costed out to run like clockwork. In contrast, the Hubble Space Telescope (fig. 4) has had a sporadic history—on again, off again—over a period of 40 years. It was championed by one person, Dr. Lyman Spitzer, from 1940 to 1950. Project Stratosphere, a prototype 12-inch telescope carried by balloon, was launched in the 1950s. NASA took over in the 1960s and successfully launched two precursor observation launches. Finally completed and launched in April 1990 at the cost of $1.5 billion, more than three times the original projected cost of $435 million, the Hubble telescope has been riddled with difficulties, including the discovery that one of the mirrors was apparently ground to the wrong curvature. Yet the vision remained the same throughout (Wilford 1990c).

Dr. Lyman Spitzer, now 75, wrote in his first proposal for a space telescope over 40 years ago that, "The chief contribution of such a radically new and more powerful instrument would be, not to supplement our present ideas of the universe we live in, but rather to uncover new phenomena not yet imagined, and perhaps to modify profoundly our basic concepts of space and time" (Wilford 1990c).

Under the vision of spacefaring, this project might be regarded as a disaster, because the spacefaring vision focuses on the quality of the journey. In fact, the journey was terrible. The project was subject to numerous postponements, overruns, and delays, and it still (1990) has serious problems even after launch. Yet when the first insightful photograph returns from the telescope, if one of the answers to the three key questions—How fast is the universe expanding? How old is the universe? What is the fate of the universe?—is disclosed, then, under the secret-uncovering vision, this project will have been a tremendous success.

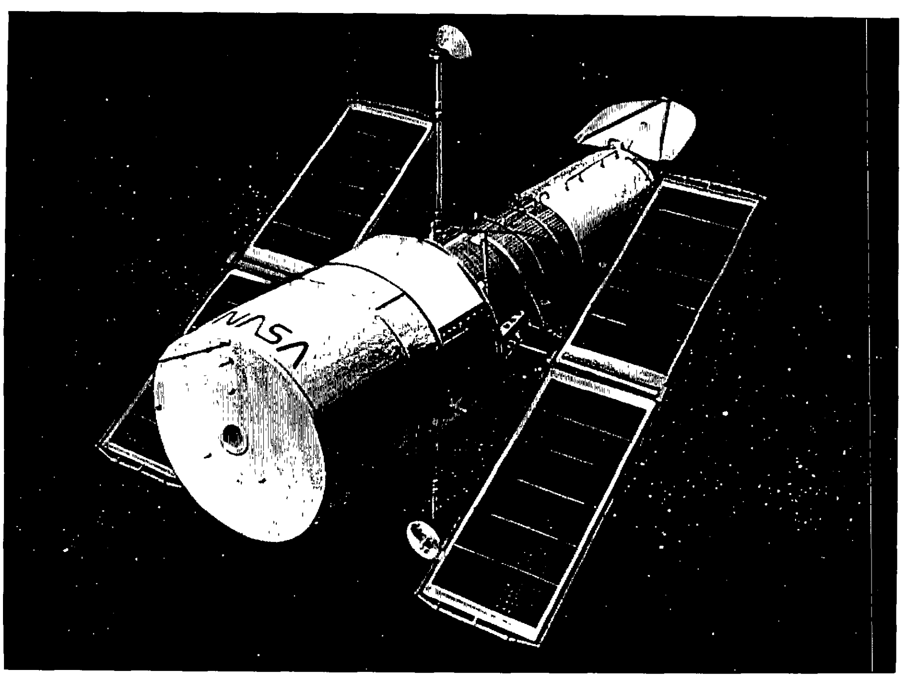


Figure 4

The Hubble Space Telescope

Section 2: Scoping a Strategically Significant Mission Agenda

The space program promises to provide a chance to restore Planet Earth to abundant health, a running start on technology leaps beyond our imagination, and access to boundless resources.

> The U.S. space program is not the only driver of U.S. technology . . . but [it] is a direct and major driver of those kinds of technologies that will drive the world market of the next century. (Anderson 1988)

> The Space Industry will be a leading indicator of all other industries in the future—Yukiko Minato, Ministry of International Trade and Industry, Japan. (Buell 1987)

> In the long term, a key to humanity's continued evolution will be the penetration of space and the economic and scientific exploitation of the solar system's inexhaustible resources and unique physical characteristics. (Glaser 1989)

The United States has been a trailblazer in space development. Since the heady days of Apollo, the United States has enjoyed a reputation for unprecedented large-scale project management expertise, long-lasting unmanned planetary exploration, a deep institutional experience base in NASA, and unparalleled aerospace leadership—all decisive competitive advantages that have benefited commercial, as well as public endeavors.

However, 20 to 30 years ago, space exploration and development programs were narrowly focused. The science and engineering problems faced today, such as alloys, fuels, distances, are much more complex than those wrestled with during the Apollo Program. A strategy needs to be formulated that effectively allocates finite resources among carefully selected objectives in a sequence that maximizes results. Important strategic insights can be derived from examining several potential mission scenarios for NASA.

Remarkably, a close examination of NASA demonstrates that the agency has been active in promoting and nurturing initiatives across the board—in every strategic space development segment. President Bush seems to want to continue a tradition of independent, full-scale initiatives. While the notion of international participation was not entirely absent from Bush's July 20, 1989, speech, it was heavily overshadowed by a nationalistic message: "What Americans dream Americans can do." We should pursue these goals "because it is America's destiny to lead." This phrasing suggests that America is going to pay the first 100 percent, and, if others want to add on top of that, they can (Chandler 1989). Such a posture needs careful evaluation.

This paper reviews three segmentations of the space development arena to demonstrate potential areas of strategic leverage for NASA, as the agency seeks to clarify its role and function within the global space development industry:

1. Consumer-driven innovation: The entrepreneurial traits of customer-driven innovation and incessant scrutiny of the marketplace are essential components of effective market-focused strategy development. The only real "consumers" of the space program are the citizens of Planet Earth. It is eminently wise to focus on their needs as buyers—their higher needs for a healthy planet for their children and their children's children. The ability to scrutinize profoundly the resource components of Planet Earth and to begin to understand the interaction of economic and natural variables promises to provide a contribution by NASA and other national space agencies around the world that is unprecedented.

2. Capability-driven innovation: There are specific gaps in our tools, products, and processes that prevent prompt exploitation of space. Nothing short of major technological leaps must be masterminded. The originators of such technological breakthroughs have typically seen them spin off into lucrative commercial ventures.

3. Destination-driven innovation: The prospect of setting up colonies on such forbidding planetary bodies as the Moon and Mars makes sense only when the colony is viewed as a base from which to exploit resources. To access the rich resources of our neighboring planets, to capitalize on manufacturing breakthroughs achieved only in low-gravity conditions, to test the possibility of transferring some of our heavily polluting industries off Planet Earth (taking care not to pollute our neighboring planets)—these tasks require a supporting infrastructure that includes the advancement of megaproject management expertise. The colonization of the Moon and Mars effectively requires the creation of entirely new industry and infrastructure sectors, which will invariably have a profound impact on our lifestyle and business approaches on Earth.

In 1988 the National Academy of Sciences recommended that the United States undertake a multibillion-dollar space science initiative that would redirect the U.S. space program in the early 21st century. They recommended that

1. An intense, continuous program be established to monitor Earth's climate, resources, and numerous other factors important to the planet's health.

2. A search for planets in distant solar systems be given a high priority.

3. A number of sample-return missions be sent to nearby space bodies.

4. Many new missions in space biology and medicine be undertaken.

The first recommendation supports the Mission to Planet Earth, the second and third support exploration efforts which are preliminary to selecting a destination, and the fourth recommendation encourages regenerative life support technology—a capability to be developed. These proposals, in the report "Space Science in the 21st Century—Imperatives for Decades 1995-2015," would require NASA's budget to grow significantly (Covault 1988).

Consumer-Driven Innovation: The Business of Protecting Planet Earth

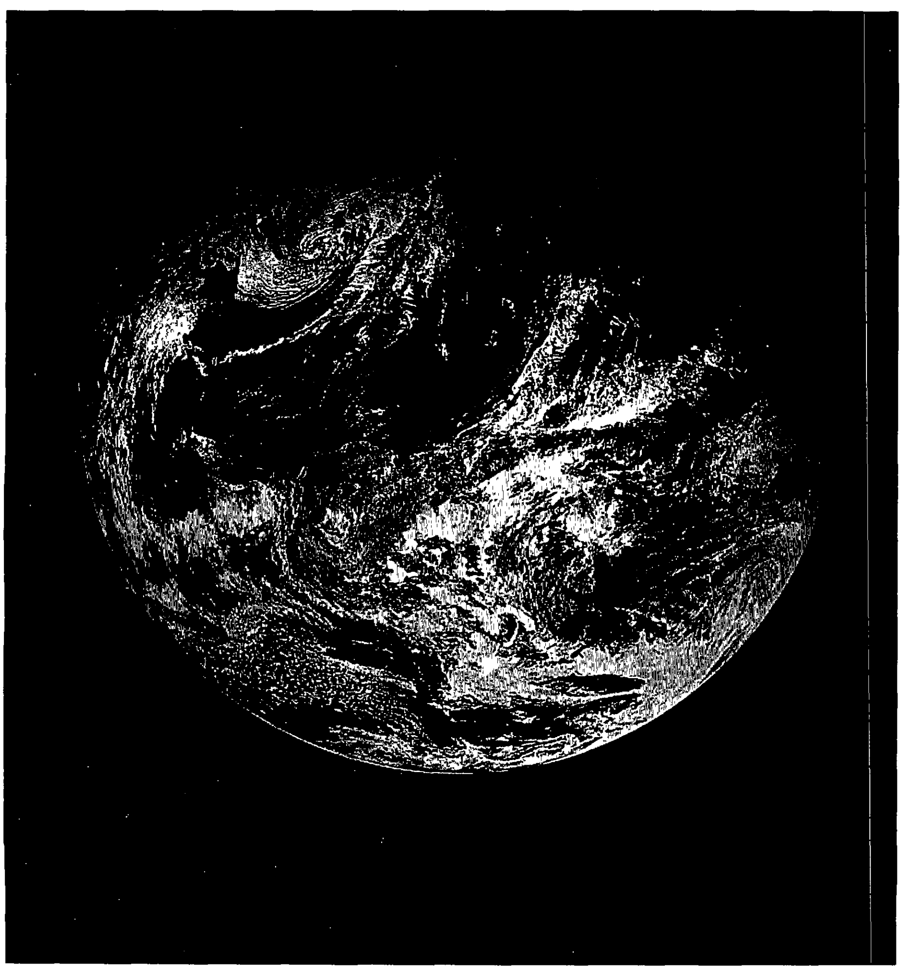
The "Planet Earth" consumer is literally consuming the planet:

> Consider the situation we face on the eve of the 1990s: We are generating waste, both solid and hazardous, at a rate far exceeding our ability to dispose of it; global temperatures are inching upwards; our protective shield of ozone is disappearing at the same time as the earthbound, harmful ozone continues to exceed safe levels in many of our cities; acid rain is killing much of our aquatic flora and fauna and damaging many of our forests; and the world population has reached 5 billion and continues to climb rapidly. (Glass 1989)

More alarmingly, further growth is essential: A fivefold to tenfold increase in economic activity is required over the next 50 years to meet the needs and aspirations of the world population and reduce poverty. This will place a colossal new burden on the ecosphere (MacNeil 1989).

Space science has already proven that it can contribute substantially to our understanding of Earth's problems: the greenhouse effect on Venus and ozone depletion on

Mars provided insights that alerted us to potential dangers in our own atmosphere. Imagine how potent direct focus by the international space establishment on Planet Earth promises to be. The Apollo 8 photo of our planet afloat in space showed us that, as Buckminster Fuller put it, we are passengers on Spaceship Earth. The Earth is all we've got—at least for now.



All products brought to market on Planet Earth follow a similar activity flow from analyzing the market and customer need, through designing the product, purchasing or sourcing the raw materials, and manufacturing, to distributing and selling the product (see table 2). There are three critical roles that NASA could play in the United States, other national space agencies could play in their respective countries, and all these agencies could play jointly on Planet Earth to align business activities with ecology-preserving systems:

- Provide an information base for delimiting constructive and destructive use of resources on Planet Earth.

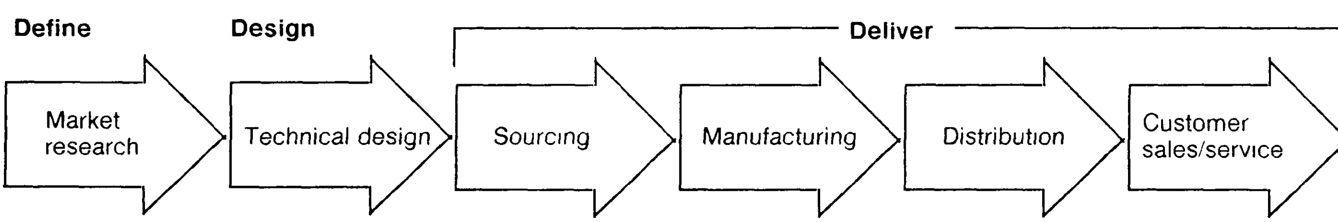
- Provide technology design initiatives that demonstrate regard for ecological limitations.

- Participate in policy formulation efforts intended to promote global industrial restructuring—including consideration of transferring the most polluting industrial activities to off-planet locations.

Market Research: Point the way to save the planet

Growth must be structured in ways that keep its enormous potential for environmental transformation within safe limits—limits which are yet to be determined. Clearly defining the parameters within which Planet Earth can be restored to health can provide powerful directives. For example, one author states that to stabilize concentrations of carbon dioxide at present levels, an immediate reduction in global manmade emissions—chiefly from the burning of such fossil fuels as coal and oil—by 60 to 80 percent would be necessary (Shabecoff 1990a).

TABLE 2. *The Business System for Bringing a Product to Market on Planet Earth*



NASA has a project under way which may identify just such degrees of tolerance: The Mission to Planet Earth is a "global habitability mission" (Brown 1989) involving a very substantial purely scientific component directed toward real human problems. It is intended to point the way to save the planet. Also referred to as Earth Observing System (EOS), it is an international initiative consisting of five giant orbiting platforms [two from NASA, two from the European Space Agency (ESA), and one from the National Space Development Agency (NASDA) of Japan], each carrying the largest and most sophisticated array of remote-sensing instruments ever assembled. The mission will begin a 15-year period of observation in the mid-1990s. This will become one of the largest space science projects ever, costing the United States $1 billion per year (Cook 1989).

The list of critical processes that impact Planet Earth's ecological system and must be monitored is extensive, including changes in concentrations of greenhouse gases and their impact on temperature; the effect of ocean circulation on the timing and distribution of climatic changes; the role of vegetation in regulating the flux of water between land and atmosphere; global circulation and processing of major chemical elements such as carbon, oxygen, nitrogen, phosphorus, and sulfur—principal components of life—as well as carbon dioxide, methane, and nitrous oxide (More than 70 000 chemicals synthesized by humans affect the global environment.); and processes of evaporation and precipitation, runoff and circulation (Clark 1989).

The end product of this international undertaking will be an information base for decision-making—the findings of scientific research and planetary monitoring. It is hoped that the environmental impact of business decisions will be demonstrated in a fact-based manner. The real environmental costs of human activities have not been isolated to date; thus, calculations of business efficiencies have been skewed in favor of the convenient. The dilemma involved in choosing process technologies, governed as they are now by private, generally short-term, profit-maximizing responses to market forces rather than long-term concerns about environmental quality, could more effectively be resolved with the data base that Mission to Planet Earth promises to assemble.

President Bush has expressed his willingness to prevent compromise while appreciating the need to redefine business standards in the marketplace: "To those who suggest we're only trying to balance economic growth and environmental protection, I say they miss the point. We are calling for an entirely new way of thinking, to achieve both while compromising neither, by applying the power of the marketplace in the service of the environment" (Shabecoff 1990b).

Technical Design: Define environmentally safe products and processes

Technologies that can be utilized on the scale necessary to support sustainable economic development must be resource-conserving, pollution-preventing, and environment-restoring, and themselves economically supportable. Sheer invention is the only effective way out of our major ecological problems, as the very technological foundations of our economy need to be totally revised. What we need is an economy that will not consume scarce resources and will not generate pollution.

Begin with the environmental constraints and then design the product: NASA is initiating a process that it believes may serve as a model for government, industry, and environmental groups. Its cornerstone is getting together before a technology is developed to determine what technological advances must be made to render a product or process environmentally and economically acceptable. Looking at the environmental issues ahead of hardware issues, they have even gone one step further: they have resolved not to develop the product or process if the environment is compromised (Leary 1990). In the case in point—development of a high-speed passenger plane—walking away would be enormously difficult, as competition stands in the wings: Aerospatiale, the French aircraft company, is studying the next-generation supersonic transport to replace the Concorde; the Japanese government has begun serious research; and the Soviet Union has begun studies on a transport plane that could fly at 5 times the speed of sound (Leary 1990).

Preliminary studies commissioned by NASA indicate that building such an aircraft is possible. However, current aircraft technology, including the best materials and engines, could not produce an acceptable aircraft, according to Boeing. The Lawrence Livermore National Laboratory concurs, having calculated that a fleet of 500 supersonic airliners using existing engine technology would seriously deplete the ozone layer by 15 to 20 percent, almost 3 times the damage from chlorofluorocarbons. NASA plans to spend $284 million over the next 5 years to find out whether the required technological advances to develop an environmentally safe high-speed plane can be achieved. The program will center initially on airport noise, sonic booms, and engine emissions that could reduce the atmosphere's protective ozone layer (Leary 1990).

Experiment with new processes that will protect the environment:

- Ecologically safe life support is being pioneered in the Biosphere II Project, a complete environment contained under 3 acres of glass (see fig. 5). Billed as the most exciting scientific experiment since the lunar landing, the airtight structure will contain 20 000 square feet of farm, where all the food will be grown. There will also be a desert, ocean, marsh, savannah, and rainforest (with 3800 species from ladybugs and shrimp to fowl and deer), laboratory, library, and apartments. Eight scientists will spend 2 uninterrupted years inside the project, which is designed to simulate life in a space colony, beginning in September 1990 (Dawson 1989). Biosphere II is a private, profit-oriented project operated by Space Biospheres Ventures. Most of the $37 million for the 4-year-old enterprise has been donated by Texas multimillionaire Edward Bass (Steacy 1988). The intent is to restore environmentally damaged areas on Planet Earth as well as advance NASA's exploratory programs. Techniques under development include chemical-free farming, natural pest-removers, crop rotation, and new ways to recycle nutrients through the soil and purify both air and water. The entrepreneurs believe that an ecological industry can turn a profit and that working with the flow of nature should cost less in the long run. They expect to market the new methods and equipment they are developing.

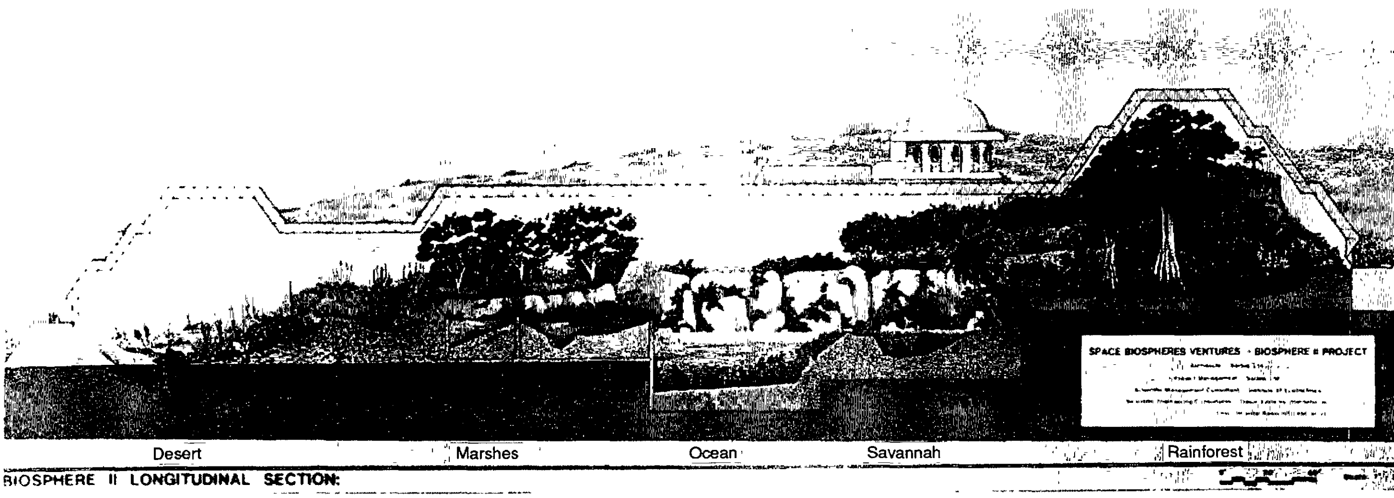


Figure 5

Biosphere II

This huge terrarium was built near Tucson with private financing in 1989 and will be occupied by a collection of 3800 species (including eight Homo sapiens*) for an uninterrupted 2-year period starting in 1990.*

The 3-acre, airtight, glass and frame structure includes five wilderness biomes. From a mountain in the center of the rainforest, a stream cascades down a waterfall and across the forest floor. It flows along a savannah, at the top of the rock cliffs, through fresh- and saltwater marshes to a 25-foot-deep ocean, which encompasses a coral reef. A thornscrub forest makes the transition between the savannah and a desert, the biome that most nearly matches the external environment.

Behind the wilderness biomes in this view are the 24 000-square-foot intensive agriculture biome and the six-story, domed human habitat biome. The natural processes in Biosphere II will be artificially assisted by two "lungs," to accommodate warm air expansion, which would otherwise blow out glass panes or break the seals, and by air and water circulation systems, because the unit is not large enough to generate weather processes.

Its developers believe that not only is such a controlled ecological life support system applicable to future space colonies but also the techniques developed such as chemical-free farming may be useful in restoring to environmental health parts of Biosphere I—our Planet Earth.

- Ecologically safe power generation can be achieved by generating power via satellites for use on the ground as well as in space. The feasibility of new solar power technologies to collect and beam power between objects in space and the Earth needs to be tested. It is not yet clear which orbits and which portions of the electromagnetic spectrum would best be used to transmit energy to Earth from space (Glaser 1989).

- Ecologically safe waste treatment can be achieved through transfer of a NASA-developed technology to Planet Earth municipalities. The NASA Technology Utilization Office, which encourages non-space applications of technology developed by NASA, transferred the first Planet Earth application of the artificial marsh filtering system (intended to treat wastewater in space colonies—research began in 1971) to a local municipality in Haughton, Louisiana, in 1986. An 11-acre lagoon and a 70- by 900-foot gravel bed with rooted aquatic plants were set up (see fig. 6). Highly effective (bacterial levels were far below permitted limits), the process was also found to be highly cost-effective (only a fraction of the cost of the conventional approach). Presently 15 to 20 systems are on-line or in the design phase throughout the United States (Dawson 1989).

Figure 6

Natural Wastewater Treatment

At Haughton, Louisiana, town officials installed a second-generation version of NASA's natural wastewater treatment system. The raw wastewater is pumped into the lagoon, where floating water hyacinths digest enormous amounts of pollutants. Then the water flows over a rock bed populated by microbes that cleanse the water further. Aquatic plants growing in the gravel bed—bulrushes in the foreground and canna lilies in the background—absorb more pollutants and help deodorize the sewage. Although water hyacinths are limited to warm climates and fresh water, bulrushes and canna lilies can tolerate both cold and salt water.

It is important to note that a rash of new product innovations could foster economic growth at levels unseen to date.

Sourcing/Manufacturing/ Distribution: Spearhead global industrial restructuring

All of our activities have environmental consequences, and all of our activities must be changed rapidly if our rendezvous with disaster is to be halted.

> The challenge facing humanity in the '90s is to reverse the environmental degradation of the planet before it leads to economic decline. . . . Meeting this challenge requires more than fine-tuning; it will take a fundamental restructuring of the global economy. (Brown 1990)

Any blueprint for an environmentally sustainable global economy would require the following.

Eliminate sources of pollution: Some pollutants have been successfully removed from the atmosphere. In each case—lead, DDT, PCBs, strontium 90—substantial improvement was achieved not by tacking a control device onto the process that generates the pollutant but by eliminating the pollutant from the production process itself (Commoner 1990).

Replace environmentally assaulting production technologies with inherently pollution-free processes: Ecologically and economically sound technologies do exist.

- If farmers would shift to organic agriculture, the rising tide of agricultural chemicals that now pollute water supplies would be reversed and food would be free of pesticide-derived carcinogens.
- If automobiles were powered by stratified-charge engines, which sharply reduce nitrogen oxide emissions, the urban pall of photochemical smog and ozone—which is triggered by nitrogen oxides—would be lifted.
- If electricity were produced by photovoltaic cells, directly from sunlight, the air could be freed of the noxious pollutants generated by conventional power plants.
- If the use of plastics were limited to those products for which they are essential, we could push back the petrochemical industry's toxic invasion of the environment. (Commoner 1990)

Consider transferring the major eroders of Planet Earth off planet: The components of growth and globalization of human activity that have had the greatest impact on the environment from 1850 to the present are agriculture, the dominant agent of global land transformation—9 million square kilometers of surface has been converted to cropland; energy, which has risen by a factor of 80; manufacturing, which has increased a hundredfold in 100 years; and basic metals, which has experienced a long-term growth greater than 3 percent per year. Each of these could conceivably be transferred off Planet Earth: agriculture, using biosphere or hydroponic techniques; energy, using solar power transmission to the Earth; manufacturing, possibly using robots on the Moon; and mining of basic metals on the Moon, asteroids, or Mars. What better justification for going to the Moon or Mars than to make life better for the Planet Earth consumer!

Eliminate indifferent public policies: Current public policies have been found to actively encourage deforestation, desertification, destruction of habitat and species, and decline of air and water quality (Clark 1989). Mechanisms, both national and international, need to be developed to coordinate managerial activities pertaining to ecologically safe industrial restructuring. Local development actions have cumulative results on the global environment that are difficult to communicate, short of demonstrating them from a vantage point in low Earth orbit. Science can help, but it is efforts that go beyond science to formulating adaptive policies that encompass environmental surprises which will ultimately determine our effectiveness as managers of Planet Earth.

Capability-Driven Innovation: The Process of Engineering Critical Technological Advances

> Science seemed at its birth to be but superfluity and fantasy, the product of an exuberant overflow of inward activity beyond the sphere of the material necessities of life, the fruit of the curiosity of dreamers and idlers. Then, little by little, it achieved an importance and an effectiveness. . . . We who live in a world which it revolutionized acknowledge its social significance and sometimes even make it the object of a cult. Nevertheless we still leave it to grow as best it can, hardly tending to it at all, like those wild plants whose fruits are plucked by primitive peoples in their forests.
> (de Chardin 1972, p. 129)

Our technological capabilities have not yet reached a level that facilitates realization of our loftiest goals. And the level of technological capability determines the effectiveness of our efforts and their cost efficiencies. We cannot mobilize a program to colonize the Moon or Mars within the next 3-5 years, for example, precisely because our current technology makes it economically infeasible. Getting materials and people into space simply costs too much; we don't know what's there—except on a superficial level—or how it can be used; and we are not sure that we can remain alive for any extended period of time, let alone return to Earth without having been debilitated in some way. The most critical impediments to space exploration are the lack of cost-effective means to leave the pull of the Earth's gravity, the availability of only a rudimentary controlled ecological life support system, and the inability to conduct research on space phenomena in enough depth to develop innovative products and processes (table 3). These are effectively the independent variables—or the problems whose resolution will facilitate a broad range of subsequent projects and programs.

TABLE 3. *Priority Issues in a Space Technology Development Program*

Independent variables	Dependent variables
Getting into space: launch vehicle economics (highly competitive)	Vehicle size Cargo capacity Fuel type
Living healthily in space: sustainable life support systems	Length of stay in space Distance travelable
Working productively in space: facility in which to experiment (ex., space station)	Development of new products & processes for commercial manufacturing Renewable power supply

Intervening variables (could significantly change the game rules)
Discovery of other life in the universe, perhaps more intelligent (and therefore having many capabilities already in hand) or distant (thus changing our target destination)
Major breakthroughs in speed of travel, perhaps rendering Mars less interesting (because we can go farther) or more interesting (because we can get there faster)
Inability to sustain life on a long-term basis outside of Earth's atmosphere, or prohibitive hardship in doing so

The National Research Council, an arm of the congressionally chartered National Academy of Sciences, believes that it is vital that Moon-Mars missions have "the capability to send humans into space, maintain them in a physical condition that permits them to work productively, and return them to Earth in good health." It has not been demonstrated that after long-duration space flight individuals can readjust rapidly to gravity without serious physiological consequences ("U.S. Panel" 1990).

One way to ensure that the effort is sustained is to make sure that the basics are in place: to focus for a time on technology development, to reduce the operational costs of spacefaring and to establish the facilities and systems—the infrastructure—that a serious program requires (Sawyer 1989). To respond to existing technology constraints, to be able to break through the current quality/cost parameters, we need to develop a targeted, thoughtful technology advancement program. A segmentation based on capabilities in hand, and capabilities required, brings to the surface the major technology gaps to be bridged (table 4). Mastery of these technologies is most likely to open up space activities to the broadest possible constituency. When the costs of getting into space, surviving in space, and producing in space are sufficiently reduced, an infrastructure can be built to nurture the wealth-generating efforts of small entrepreneurs and independent individuals, as well as major corporations and governmental agencies.

TABLE 4. *U.S. Mission Scenarios: Capability-Driven Innovation*

Capability	Technological impediments	Proposed projects/requirements
Space transportation	Economic access to space	• Shuttle C unmanned cargo version of Space Shuttle • New generaton heavy lift rocket, to lift 300 000 lb + • Aerospace plane—advanced propulsion, horizontal take-off • Civil Space Technology Institute (CSTI), to increase operating margins of propulsion hardware
	Maneuverability in orbit	• Exploration Technologies R&D Program, to develop technology for operations beyond Earth orbit • Develop two orbital vehicles • Develop in-space assembly capability • Develop system for storing propellants in Earth orbit for later use • Develop small, reusable moonship that separates into lander and orbiting module • Develop accurate and safe autonomous landing, rendezvous, and docking and sample retrieval
	Deep space travel	• Develop a rocket powerful enough to reach Mars
Advanced technology	Sufficient power supply	• Construct energy forms to beam power to Earth (NASA Lewis/Harris solar concentrator) • Develop space-based nuclear reactors (JPL SP-100; Westinghouse Multimegawatt Space Nuclear Power Supply) • Mine the Moon for alternative energy sources • Develop advanced chemical propulsion
	Automation and robotics breakthroughs	• Develop advanced "intelligent systems" technology to reduce cost of unmanned probes
	Advanced data and computer system breakthroughs	• Develop advanced computer technology to reduce cost of unmanned probes

TABLE 4 *(concluded)*.

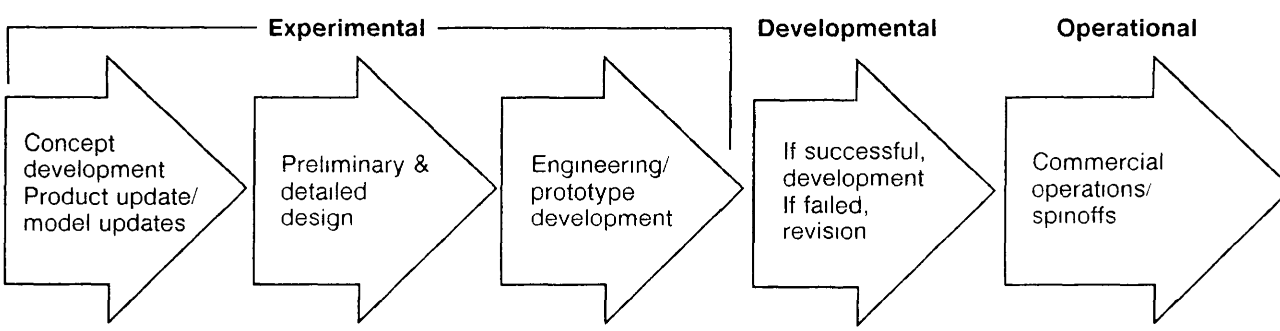
Capability	Technological impediments	Proposed projects/requirements
Life sciences	Substitute gravity	• Modify the impact of microgravity on human systems by exercise, artificial gravity, autogenic feedback training, and nutrition (NASA Ames) • Understand interdependence of musculoskeletal, cardiovascular, and endocrine systems in low and artificial gravity (Space Station *Freedom*) • Determine the effects of extended weightlessness on humans
	Sustainable food supply	• Experiment with hydroponics space farm that uses nutrient-rich solutions instead of soil • Develop self-sustaining system from growing fruits and vegetables in space
	Closed water/waste treatment system	• Biosphere II, a complete environment under 3 acres of glass • Controlled ecological life support system (CELSS) • Bioregenerative life support to generate oxygen, supply fresh food, remove excess carbon dioxide
	Shelter	• Develop building materials and alloys from lunar ore • Test use of spherical inflatable housing structure made of Kevlar (Lawrence Livermore Natl. Lab)
	Oxygen	• Extract oxygen from lunar materials for use in life support systems and as propellant
	Remote health care	• Develop clinical health maintenance facility

Sources: Berry 1989, Covault 1989d; "Gardens in Space," Los Angeles *Times* 4-2-89, Harford 1989, Henderson 1989, Sawyer 1989; Westinghouse 1989.

The funding requirements to achieve such technological advances are difficult to estimate: A dichotomy exists between the cost to make the leap and the cost savings achieved as a result of the leap. Since the breakthrough has not yet been achieved, it is impossible to predict how many false starts must be surmounted in the struggle up the learning curve to success (table 5). Such development does not necessarily follow a straight line; it is often a series of iterations, evolutionary in its unfolding. Because these "technological leap" projects cannot even guarantee that success will be attained, they are by definition high-risk. However, achievement of the breakthrough provides enormous rewards to the technology owner and permanently redefines the competitive arena to the advantage of the breakthrough innovator. Because the efforts are often very expensive, they are increasingly undertaken on an industry-wide basis; because the results can be very lucrative, they are often kept secret from other nations—guarded like the national treasures they are.

TABLE 5. *The Life Cycle of a Technological Breakthrough*

Phases



Cost exposure can be reduced through partnerships among government agencies, industry, academia, and entrepreneurs from the same country—or via international partnerships. When a government participates in a project, supported by public financing, the results of the activity are typically in the public domain. Alternatively, government agencies may fund corporations and entrepreneurial companies conducting research and developing products, often with the understanding that what they learn in the process can be privately held and spun off into commercial products.

A review of the national space development strategies of selected countries reveals that while the United States is launching initiatives in a broad range of arenas (manned and unmanned), most of the other major participants, with the exception of the Soviet Union, have restricted their immediate goals to profitable commercial applications while seeking independence in space as a long-term objective (table 6). This suggests that European, Japanese, and other participants are viewing space development from a highly competitive, commercial vantage point. While they are seeking full autonomy in space, they are willing to joint venture in the short term (they say) in order to catch up. Overall, space is viewed as a terrain in which major technological leads can be developed and sustained.

TABLE 6. *National Space Development Strategies: A Comparison*

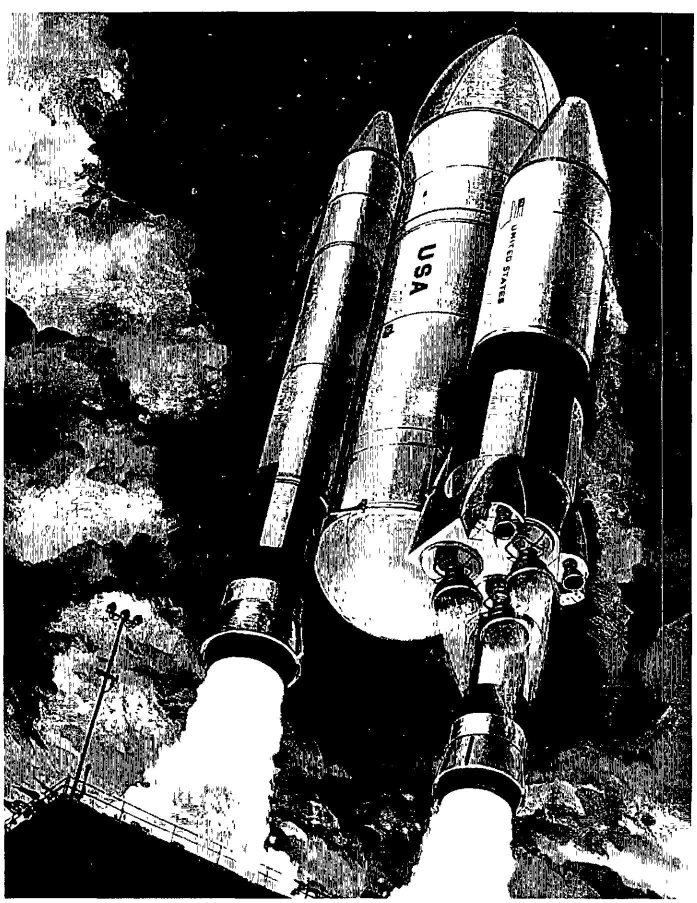
Country/agency	Focus	Philosophy	Strengths/weaknesses
U.S A./NASA	Unmanned exploration Manned spacefaring	Massive technological leaps in R&D objectives	Bush commitment to take a fresh look Continually changing vision/funding
U.S.S.R.	Put man on Mars within next 25 years	Gradual development of space capabilities	Management sharply criticized
Europe/ESA	Propulsion technologies	Full autonomy in space by year 2000	Reluctant to commit financing Has technical ability to be a major space power but seems to lack political will required to achieve most cost-effective results
Japan/ NASDA ($1.1 billion) Institute of Space & Astronautical Sciences ($114 million)	Commercial-ization	Good space science doesn't need to be expensive	Heavily subsidized by Japanese private companies A late start because no military expenditure, but reshaping program for 1990s
Canada/Canadian Space Agency ($1 billion +)	Robotics	Cooperate to participate in new technology development	Robotics a Canadian strength Target strategic technologies that make possible the mission-critical mobile servicing system
India/Indian Space Research Organization (ISRO)	Commercial-ization	Attract industry through divesting management & technical operation of selected facilities to industry	Guarantees 15% profit margin on projects Encourages honing technical skills Deemed "export," entitles suppliers to huge tax concessions

Sources Bennett 1987, De Cotret 1988, Gibson 1984, Kapur 1987, Lenorovitz 1988a, b, c, "Soviets Put Craft," New York *Times* 1-30-89

This focus on capability development may appear low-key to the general public when compared to more visible Moon or Mars projects, because it is technology-centered and forces repetitive iterations to uncover the product or process dynamics in enough depth to engineer a major innovation. However, our success in advancing our capabilities will ensure the smooth implementation of those more visible, destination-focused projects.

Getting Into Space: Propulsion

The single most frustrating problem related to space development is the prohibitive cost of getting vehicles, materials, and people into space. Once out of Earth's gravity field, there are additional issues regarding maneuverability and propulsion through deep space. The pace of commercialization, however, depends on the pace of the launching business.



Concept for a Heavy Lift Launch Vehicle Derived from the Space Shuttle

By replacing the Shuttle's manned orbiter with a cargo carrier, the payload capacity of the space transportation system can be increased by 2-3 times over current capacity per launch. Costs should also be lower.

Figure 7

Concept for the National Aerospace Plane

Artist: Stan H. Stokes (NASA Art Program Collection)

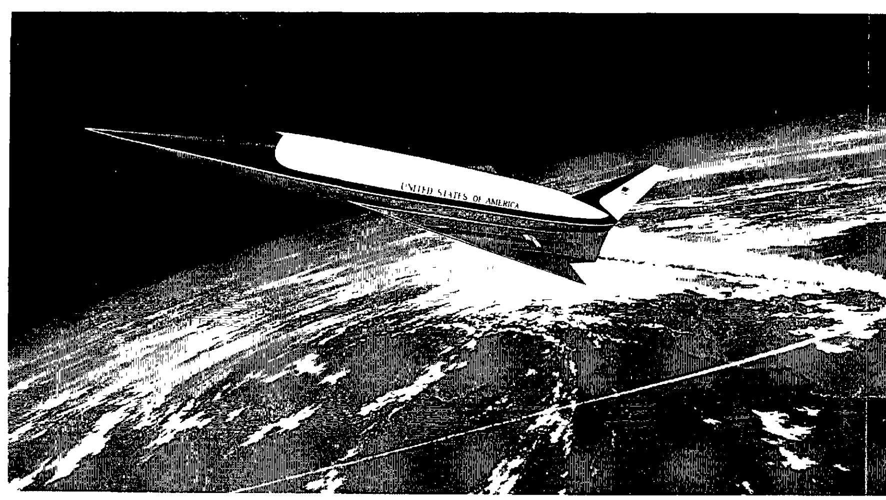
Technologies developed for the national aerospace plane (and spinoffs from that technology development) would greatly improve the competitive position of the United States in the aerospace field. This revolutionary class of vehicles would be able to take off and land horizontally on standard runways like a conventional airplane, cruise in the upper atmosphere at hypersonic speed, or fly directly into Earth orbit.

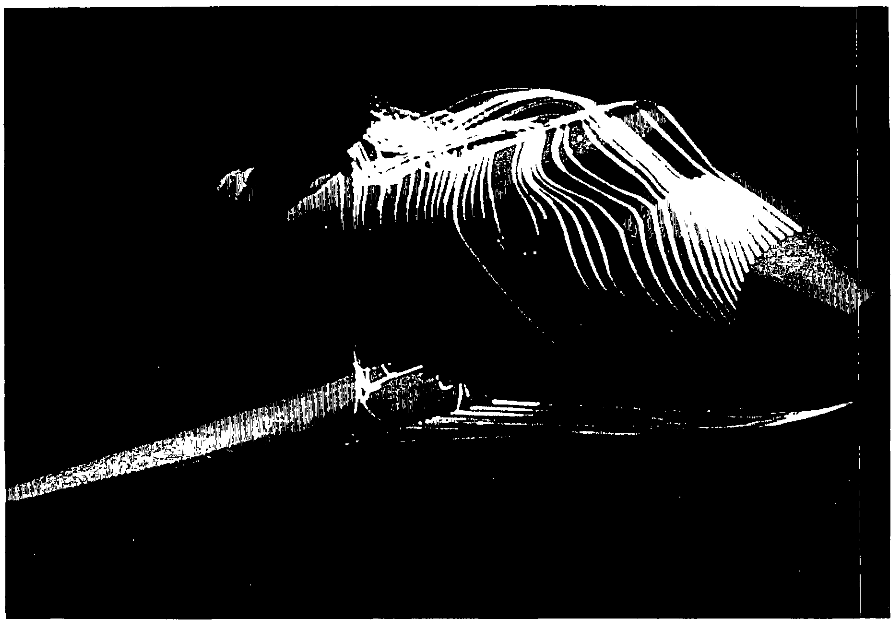
Its "scramjet" engines would burn a mixture of hydrogen and air, thus obviating the need to carry liquid oxygen. Its horizontal takeoff and landing (HOTOL) capability would eliminate the need for vertical launch facilities currently required for the Space Shuttle and unmanned boosters. These two capabilities should allow the spaceplane to deliver payloads to orbit at a fraction of today's cost.

The technologies are applicable to supersonic (above Mach 2, or 1300 mph) military transports and hypersonic (above 4000 mph) civil planes that could fly passengers from the United States to Japan in 2 hours.

The phase of the joint Department of Defense/NASA effort which began in 1986 involves development of key technologies in propulsion, aerodynamics, advanced structures, high-temperature materials, and computational fluid dynamics. Computer simulation is used to "fly" mathematical models of the national aerospace plane, which must attain 17 000 mph (Mach 25) to escape Earth's gravity and reach orbit.

Experimental—skills beyond a single organization: The most impressive propulsion project being developed today is the national aerospace plane (see fig. 7). Regarded as of profound strategic urgency, it is expected to have a major effect on the course of U.S. space and aeronautics development into the 21st century as well as a tremendous impact on American competitiveness in the aerospace field, which is our number 1 export category. A direct counter to similar efforts under way by the Europeans, the Japanese, and the Soviets, it is expected to be completed by 1997 (3 to 5 years ahead of the others).





Particle Tracings Over the Space Shuttle Imaged by NASA's Numerical Aerodynamic Simulator

The effect of hypersonic airflow upon such vehicles cannot be tested in wind tunnels, which go no higher than Mach 8. NASA's Numerical Aerodynamic Simulation Facility, located at Ames Research Center, is using Cray supercomputers to build to an eventual capability of 10 billion calculations per second. Such computational capability will not only provide enormous impetus to aerospace development but also permit major advances in other structural design, materials research, chemistry, and meteorology.

A team of private industry contractors is sharing development costs with the Government and operating as a noncompetitive consortium to share research data, keep costs down, and quicken the pace of technology.

The national aerospace plane is sure to be a major technological leap if achieved, because never before has an experimental aircraft been designed to fly so much faster and higher than any other plane (Covault 1989a). Its design parameters are to

- Achieve a speed of 17 000 mph to escape Earth's gravitational pull and reach orbit
- Circle the globe in 90 minutes
- Withstand a temperature of 3000°F
- Have engines designed to gulp oxygen from the air
- Determine the effect of hypersonic atmospheric chemistry (Lavin 1989)

Clear standards of cost-effectiveness have been defined for the national aerospace plane:

- Must be cheaper to operate than the Shuttle and require less manpower
- Must be able to use any standard airport in the world (Lavin 1989)

What is remarkable about this program is the extent of national-level, industry-wide collaboration focused on this critical technological breakthrough. Truly the best skills have been brought to bear on the task. The project team includes NASA, the Pentagon, and five U.S. aerospace companies led by the Air Force (three airframe manufacturers and two engine manufacturers). In effect, all of the major competitors in the aerospace industry have been invited to participate equally—on a level playing field. Take the development work for the heat-resistant material: None of the companies could afford to do all the research alone, so each has specialized in one type of material, sharing the results with all competitors. Discussions are under way regarding ways to collaborate in building the plane itself (Lavin 1989).

What is alarming is that our leadership in this area is not secured, and major competitors have set their sights on the same goals. The European Space Agency, representing 13 European countries, has a three-pronged space program that includes a fifth-generation Ariane heavy lift rocket, a module of Space Station *Freedom*, and three versions of the horizontal take-off and landing aircraft (table 7). This horizontal take-off technology is regarded as so critical that the Europeans cannot agree on who should lead the project, where it should be headquartered, or how it should be engineered.

TABLE 7. *European Space Agency: Three-Pronged Space Program**

Program		Scope	Participants	Est. budget
Ariane V heavy lift rocket		Liquid hydrogen & oxygen fuel Max. load 100 000 kg Will double launch capability	France 45% W. Germany 22% Italy 15% Others 18%	$3.5 billion
	Hermes piloted spaceplane	Target launch 1996-7	Avions Dassault-Breguet (engineering) Aerospatiale (coordination) (45% French funding)	$4.4 billion
"HOTOL" (Horizontal Take-Off & Landing) (three alternatives)	U.K. alternative	Upgraded version of Concorde: horizontal take-off, air-breathing engines to boost to near vertical trajectory, horizontal return	British Aerospace	
	Sanger (W. German alternative)	A small reusable spacecraft launched from back of aircraft, reaching orbit on own power, then gliding back to Earth	W. German aerospace companies	
Columbus Space Module		Part of U.S.A.-led int. space station project	13 member states	$3.7 billion

*ESA is reluctant to commit to all three key space projects.

Sources: Dickson 1986, 1987, Mordoff 1988.

Developmental—synergies and interfaces: The United States is ahead in low-cost rockets for small payloads, thanks to Orbital and other small entrepreneurial organizations. Orbital Sciences Corporation developed a 50-foot, winged rocket, the Pegasus, and launched it from a B-52 flying over the Pacific Ocean. (See figure 8.) Pegasus' winged design is a first for unmanned rockets, giving the vehicle the extra lift it needs to head toward orbit most efficiently from a horizontal airborne launch. Developed to address the needs of "microspace" (that is, smaller and more affordable rockets and satellites), it is intended to launch "lightsats," a new class of satellites. The objective of this highly focused development strategy was to provide space-oriented products and services that appeal to a wider group of governments, companies, and entrepreneurial consumers. This down-sizing effectively reduces the cost per pound of payloads in orbit, a critical factor in developing a broader based commercial space industry.

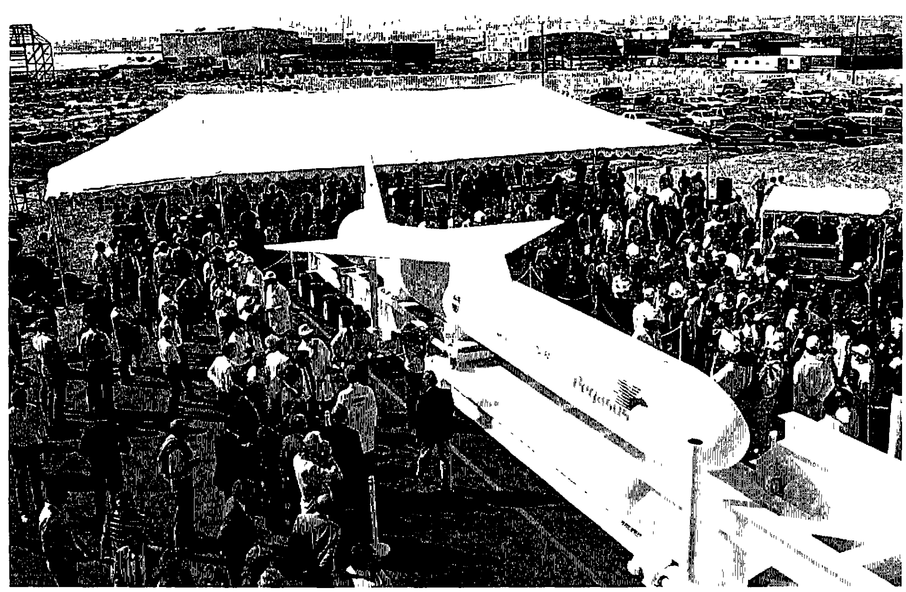


Figure 8

The Pegasus Rocket

Designed and built by Orbital Sciences Corporation and Hercules Aerospace Company and sponsored by NASA and DARPA (the Defense Advanced Research Projects Agency), this 50-foot-long, winged rocket is carried aloft by a B-52 before the first of its three motors is ignited. Its down-sizing is intended to offer much lower cost for the delivery to orbit of lightweight satellites.

Once Orbital's rocket is made operational, the company expects to sell commercial launches for \$6-7 million or \$6000 per pound of payload (versus \$20 000 per pound for small satellites carried by other lightweight payload rockets, such as the Scout rocket by LTV Corporation). It is important to observe the amount of Government support required for such entrepreneurial efforts: The Pentagon's Defense Advanced Research Projects Agency (DARPA) paid \$6.5 million to Orbital for the launching, making the project economically feasible, and NASA provided the B-52 for the launch, effectively establishing the credibility of the provider. NASA and DARPA are considered to be anchor customers—the largest and most sophisticated consumers of space products, consumers whose needs create the demand for, and define the parameters of, new products and processes to be developed (Stevenson 1990).

Operational—indicators of success: The unmanned vertical rocket launch business is an established technology, in an established industry, with heavy global competition. A \$2 billion worldwide industry, the commercial launch of satellites is forecast to continue to grow through the 1990s. As communications networks are being privatized and deregulated worldwide, even more activity can be expected (Cook and Lewis 1988).

There have been two keys to success in operating a launch business:

- The right product

Europeans believed that unmanned launchers such as Ariane would continue to offer the better solution for launching satellites that do not require the presence of astronauts. The primary goal of Arianespace was to give Europe an independent launch capability for its own satellites (Dickson 1986), but the result has been to provide a competitive advantage in the international marketplace (Lenorovitz 1988a, b, c). Ariane of Arianespace has averaged about a 50-percent share of the global launch market, also taking a share from the Space Shuttle after the *Challenger* disaster. Forty-three satellites were launched between the beginning of Ariane's commercial program, in 1981, and 1990. More than 32 launches are scheduled, as of February 1990, at a value of \$2.36 billion. Launches have been suspended twice: once in May 1986 and again in February 1990, both times to allow for inquiries into explosions of rockets in flight, destroying their satellite cargoes ("Panel To Examine" 1990). Ariane must adhere to a rapid and sustained launch rate if it is to fulfill the orders currently on its books and to compete for new business.

- The right price

The Space Shuttle, a manned vertical launch vehicle, was expected to command 75 percent of the global launch business when envisioned by Nixon in the 1970s. We were first in a market that was wide open—but with the wrong price parameters. The lower the launch cost, the broader the customer base. However, we somehow got locked into a technology that is not cost-effective. Although it has been a superb research vehicle and it has taught us how to design a reusable reentry vehicle that could bring material back from space, the overriding reason it was built was to lower costs. *Reusable* has turned out to mean "uncorrectable." The Shuttle's overhead cost is $3 billion a year, excluding the hidden costs in salaries (10 000 people are required at Cape Kennedy to launch it). At only eight or ten flights a year, the cost is at least $300 million per flight (Brown 1989). After the *Challenger* accident, President Reagan determined that private companies would handle all commercial launches (Peterson and Schares 1988).

Three U.S. companies (McDonnell Douglas, Martin Marietta, and General Dynamics) are going head to head with companies abroad for business (see table 8) and have occasionally enjoyed a cost advantage depending on the changing value of the dollar. Ariane is considered to be an equal competitor with the United States in heavy-launching capacity, and the Japanese are catching up fast.

TABLE 8. *Worldwide Commercial Launch Market, a $2 Billion Space Transportation Industry*

Company	Rocket	Payload capacity, lb (kg)	Cost/launch, $ million	Success rate, %
McDonnell Douglas	Delta II	4 000 (1800)	50	98
Martin Marietta	Titan III	10 000 (4500)	110	96
General Dynamics	Atlas-Centaur	5 200 (2400)	59	95
Ariane	IV	9 200 (4200)	85	80
China	Long March 3	4 000 (1800)	35	
U.S.S.R.	Proton	4 800 (2200)	36	
Japan	(Will begin competing in 1993)			

Sources Cook and Lewis 1988, Feder 1900, Peterson and Schares 1988

Price competition is stiff. For example, China typically beats Ariane's satellite launch price by several million dollars and usually agrees to underwrite $30-60 million insurance on the launch for a premium 15 to 20 percent below world rates (Peterson and Schares 1988) as a way of buying a larger share of the market.

Living Healthily in Space: Full functioning

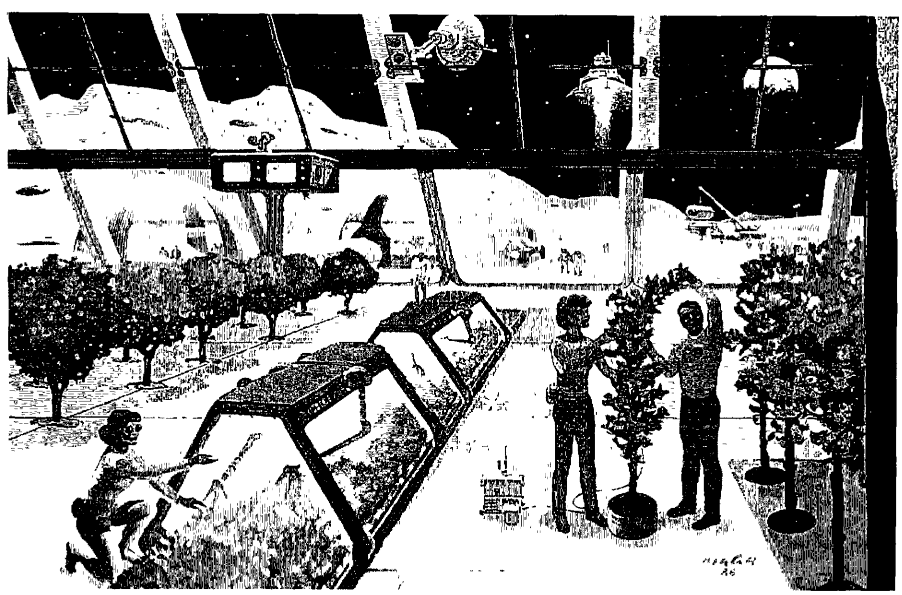
Human spacefaring is only worthwhile if it is a peak experience—that is, if really challenging and creative work can be done in space. For humans to be as productive in space as they are on Earth, their life support system must be totally integrated, leaving individuals whole and intact, so that their functions are not in any way impaired.

Life Sciences received only $124 million of NASA's $13.3 billion budget for fiscal year 1990. Without understanding the scope of research required to resolve the critical issues, it is difficult to say whether that is too little or too much. At first glance, however, it appears that life support research is less advanced than other areas of space engineering and science.

Life support: To date, it has been possible to send astronauts into space with a full stock of expendables such as air, water, and food without regeneration because of the short timeframes of the missions undertaken. Since resupply would be impossible at a location like Mars, which is 2-3 years away from Earth, resources would have to be reclaimed and reused more and more, or else mined, grown, or otherwise produced onsite. Work is under way on a partially closed air and water system for the space station, which may be sufficient for initial trips to the Moon and Mars. It may be desirable to extend the system to a self-monitored and self-controlled ecological life support system that turns metabolic and other waste into food, potable water, and a breathable atmosphere by integrating biological, physical, and chemical processes (Aaron et al. 1989).

A controlled ecological life support system (CELSS) program was initiated by NASA in the late 1970s. The long-term goal is to devise a bioregenerative support system to generate oxygen, supply fresh food, and remove excessive carbon dioxide from the station. By reducing the amount of expendables that must be carried into space, the system is expected to lower operating costs. Essentially, CELSS uses biological systems to recycle air, water, and waste products (Hubbard 1989). A physical/chemical version of this system is planned for Space Station *Freedom*. This system will recycle the water and air supply using nonbiological technology. A more advanced system which incorporates plants and food production is being explored for Moon and Mars missions.

Initial cost in terms of mass lifted into orbit will be high; but, since it is expected to function indefinitely and since it will pay for itself (that is, generate food and oxygen equal in mass to the mass of the system) in 5-7 years, the system is expected to have minimal costs over its lifetime. A benefit of a bioregenerative system is its ability to provide psychological comfort as well as supply fresh food to crews who are isolated from the Earth for a long time. Research continues on recycling, system stability, and food production (Hubbard 1989). NASA has awarded grants to universities and research centers to experiment with growing such crops as wheat, lettuce, white potatoes, sweet potatoes, soybeans, sugar beets, and peanuts under weightless conditions and under different types of artificial light ("NASA Seeks" 1988).



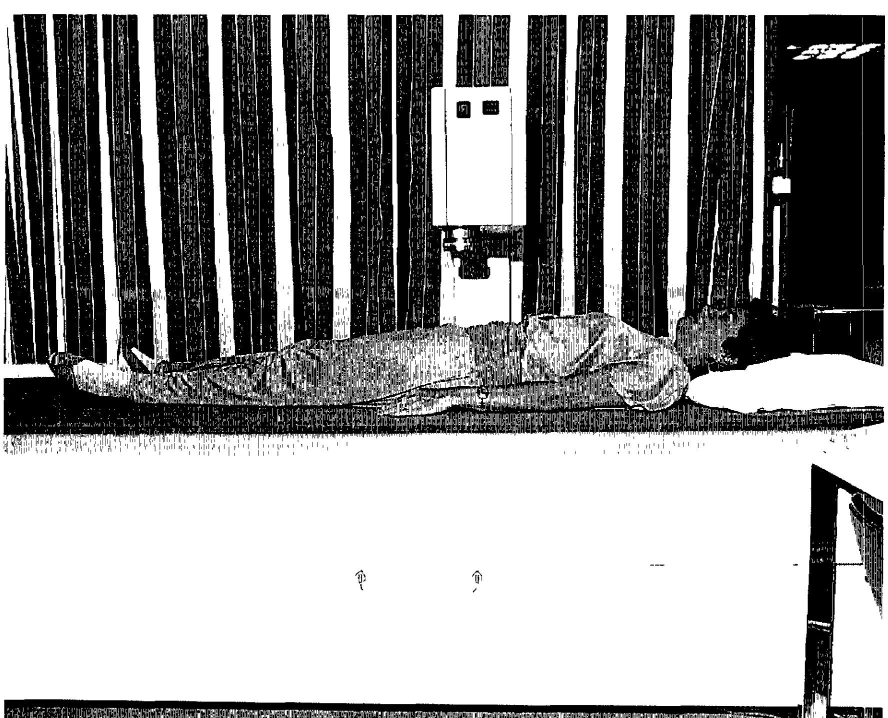
Lunar Greenhouse

Such a bioregenerative life support system might provide psychological comfort, as well as fresh food, water, and air, to crews isolated from the Earth for a long time.

Courtesy of the artist: Robert McCall

Gravity: Only one man, Yuri Romanenko, a Soviet cosmonaut, has ever been in orbit for close to a year: He took a 326-day mission in 1987. His condition upon return was quite alarming. He had significant loss of skeletal bone; he lost 15 percent of muscle volume in his legs—enough to require him to relearn to walk—despite exercise; and there are serious concerns about his heart.

Although the human body responds to microgravity with neurovestibular changes that can cause astronauts to suffer temporary disorientation and sickness during a mission, there are more serious musculoskeletal and cardiovascular effects such as loss of muscle mass, bone decalcification, and blood pooling that can cause problems in flight and after the astronauts return to gravity. Exposure to space produces biochemical and physiological changes in plants and animals from the cellular level to the whole organism.



Bone Densitometer

This total body bone densitometer measures the total calcium in the human body. Loss of calcium has been seen in astronauts and cosmonauts who have experienced weightlessness for more than a few days Such a loss has also been observed in subjects in bed rest studies (the conditions of which may more nearly resemble the reduced gravity of the Moon). The Medical Sciences Division at the Johnson Space Center is studying ways to reduce the calcium loss in space by giving subjects exercises to perform or medication or both.

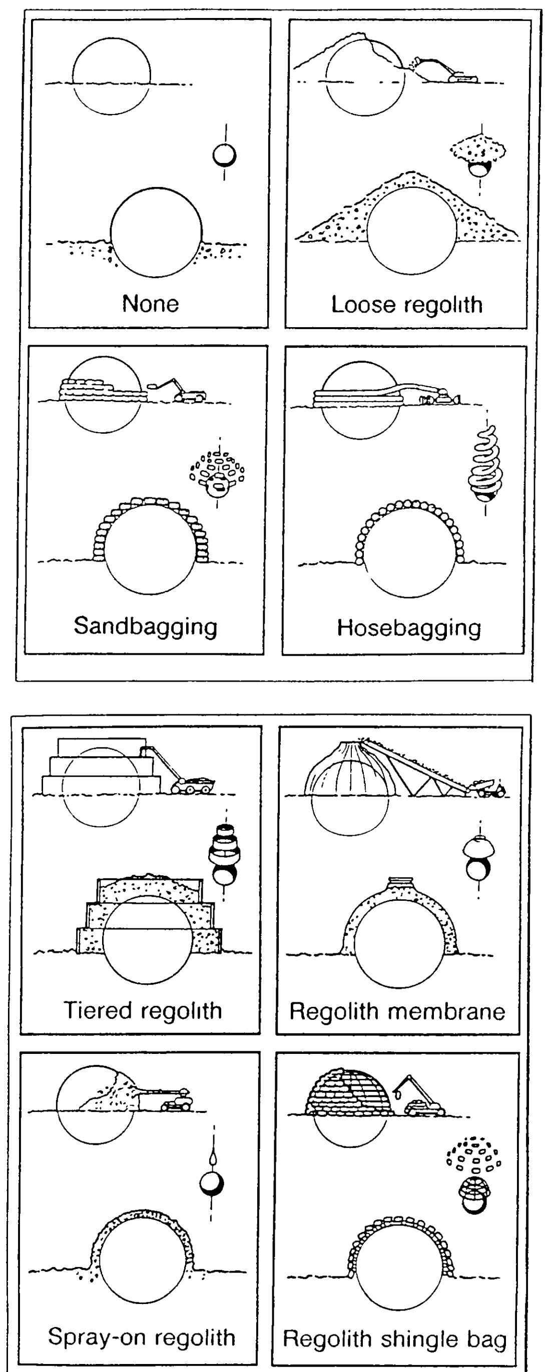
Space Station *Freedom* will have a life science research facility that will include a centrifuge system (1.8-2.5 meters in diameter) that produces an environment with gravity levels of 0.01-2.0 g. This is a first step in a program that requires acceleration devices in order to analyze the effects of microgravity and varying levels and exposure times of linear acceleration on biological systems (Hubbard 1989).

There are now serious doubts that humans can work effectively or efficiently in weightlessness for longer than 4 to 5 months. Humans cannot stay weightless in space more than about 12 months without risking permanent physical damage (Banks 1989). Since the shortest Mars trip will take 14-17 months, and the more efficient trips will take 3 years, advanced countermeasures are a must. They will probably include artificial gravity created by rotating the entire vehicle or by using a local centrifuge. Areas of further study on artificial gravity include temporary versus constant exposure, radius and rates of rotation, and the associated g loadings, side effects, and problems of transition between nonrotating and rotating environments (Aaron et al. 1989).

A goal of NASA's Ames Research Center is to extend the presence of humans in space. A growing body of data reveals an interdependence among the musculoskeletal, cardiovascular, and endocrine systems. There is an emerging interdisciplinary approach at Ames which recognizes the interrelationship of physical forces, gene expression, metabolic processes, and hormonal activity. Biomedical research, human performance, and life support systems form the core of the Ames program. How the effect of microgravity on human systems can be modified by exercise, artificial gravity, autogenic feedback training, and nutrition is under study (Hubbard 1989).

The space station's clinical health maintenance facility includes basic diagnostic and therapeutic equipment both for use in near-Earth orbit and for gauging the more demanding medical implications of exploration missions (Aaron et al. 1989).

Shelter: Shielding systems must be developed for flight as well as at the destination points. Travelers to Mars would face ionizing radiation, mostly galactic cosmic rays in interplanetary space, and might experience severe proton flux from occasional solar particle events. Shielding must protect the crew in flight, whereas burrowing or placing bags of soil atop habitats will probably protect explorers on the martian or lunar surfaces (Aaron et al. 1989).

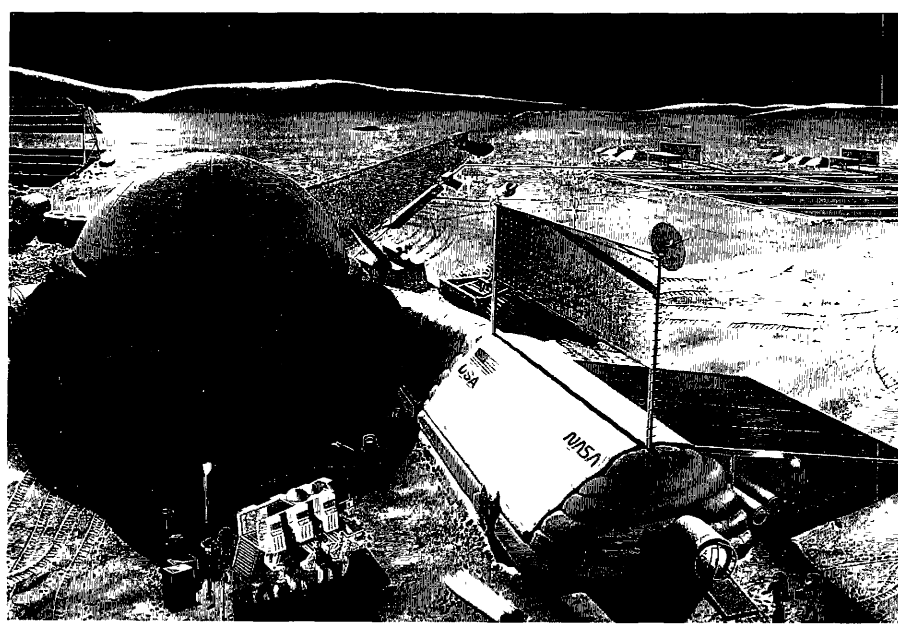


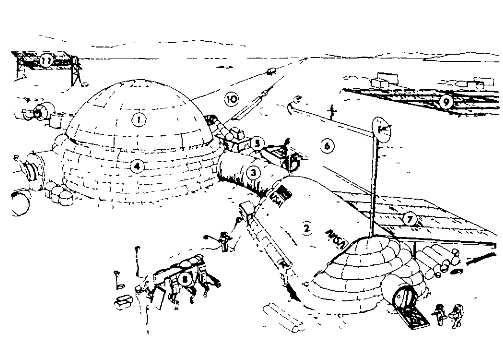
Options for Habitat Radiation Shielding

Dr. Lowell W. Wood and his group at Lawrence Livermore National Laboratory suggest building inflatable spacecraft for space stations and a Mars probe instead of the rigid metal variety now planned. The use of inflatables accounts for part of the cost savings asserted by the LLNL proposal. The drawback is that these systems would be used without testing in space and thus the risks to the crew would be much higher.

Producing in Space: Commercialization

The U. S. Commerce Department projects that space venture





Lunar Outpost

In this artist's concept of the lunar outpost described in NASA's 90-Day Study, the construction shack (foreground right) has been used as the initial habitat while the larger inflatable dome habitat was put into place, inflated, outfitted, covered with regolith for radiation shielding, and provided with solar power. In the concept proposed by Lowell Wood and his group at Lawrence Livermore National Laboratory, by contrast, the inflatable comes with all its contents already inside. It inflates automatically, and all the interior structure simply unfolds to provide rooms, plumbing, electrical circuitry, and furniture.

Artist: John Michael Stovall

1. The inflatable habitat
2. The construction shack
3. Connecting tunnel
4. Continuous, coiled regolith bags for radiation protection
5. Regolith bagging machine, coiling bags around the habitat while bulldozer scrapes loose regolith into its path
6. Thermal radiator for shack
7. Solar panel for shack
8. Experimental six-legged walker
9. Solar power system for the outpost
10. Road to landing pad
11. Solar power system for the lunar oxygen pilot plant

revenues will be about $3.3 billion per year, with a real growth of 10 percent per year. Except for communication satellites and possibly launch vehicles, commercial space development is expected to be further down the road. The Japanese project a similar market size in the near term; they believe that the market for made-in-space semiconductors, alloys, glass, ceramics, and biomedicines will top $3.5 billion per year. But they foresee considerable growth by the year 2000, perhaps even hitting $24 billion (Buell 1987).

It doesn't make sense to explore space with manned missions unless those missions hold an ultimate possibility of becoming wealth-creating. The space industry, as an infant industry, is extraordinarily high in risk and low in short-term return. NASA has taken important steps to nurture commercial interest in the program. This is essential to converting technological insights into spinoff products and processes, as well as having the network in place to support future development and expansion.

Policy formulation: NASA introduced its Commercial Space Policy (CSP) in 1982 to reduce the risks of doing business in space and to establish new links with the private sector in order to increase development. Concerns addressed by the policy included rising insurance costs, safety, and competition from the commercial interest of other space programs, such as ESA's Ariane (Lamontague 1986).

The Reagan Administration designated commercialization a basic element of the U.S. space program. A major administrative concern was to create mechanisms for ensuring fairness for companies, users, and consumers who will be entering the space business in the future. To foster a new private-sector space industry, such policy approaches as privatization, marketing of privately owned technology currently used exclusively by the Government, private development of new technology with major assistance from the Government, and private development of new products and services without major governmental assistance were introduced (Levine 1985).

Entrepreneurial seeding: U.S. business had been confined to the role of Government contractor from NASA's inception until 1984, when the Office of Commercial Programs was formed. Since then, more than half of the 50 largest U.S. industrial corporations have been participating in NASA-sponsored commercial space activities. NASA has also established an enormous technology transfer network and developed numerous joint contractual arrangements that offer flight time for applied industrial research and development (Switzer and Rae 1989). This vital role played by NASA in partnership with the private sector has enabled the U.S. program to keep ahead.

The NASA Center for Advanced Space Propulsion at the University of Tennessee Space Institute near Tullahoma is one of 16 proposed research centers to receive $5 million per year from NASA for 5 years as startup capital, after which the centers are to be financially self-sufficient. Initially focusing on studying access to space, the U.T. consortium includes

- Auburn University
- Princeton University
- University of Alabama, Huntsville
- Air Force's Arnold Engineering Development Center
- Boeing Aerospace Co.
- Calspan Corp.
- Rocketdyne
- Saturn Corp.
- Symbolics, Inc.
- Technion, Inc.

The objective of these planned consortia is to boost the United States into a competitive posture in the commercial use of space in the next century (Mordoff 1988). The early years are expected to be more research than manufacturing, with new products and processes needed for private ventures in space expected to evolve from these research efforts. To make commercialization of space more attractive, longer range projects are also planned in areas that businesses need, such as creating vacuums and growing crystals (Feder 1990).

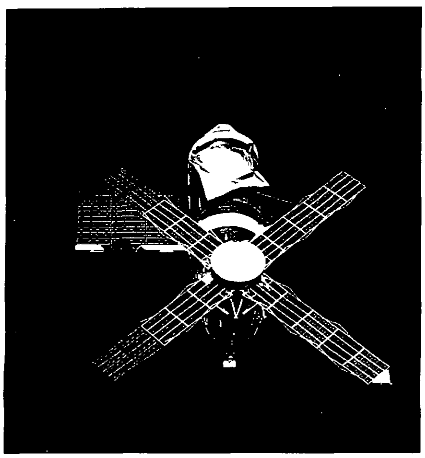
The United States is not alone in stimulating private participation: The Europeans and the Japanese are aggressively seeking opportunities to develop and provide products and processes to the global space industry.

Intospace GMBH (Hanover, West Germany), the most active and important of European space companies, is a consortium of 94 European industrial investors, mainly German giants such as Krupp, Hoechst, and Daimler-Benz. This consortium has $3 billion to spend on commercializing microgravity research (Peterson and Schares 1988). Intospace is evaluating participation in the Cosima flights' protein crystal growth missions, as well as two other research missions—Suleika (space processing of superconductive materials in microgravity) and Casimer (catalyst materials) (Mordoff 1988).

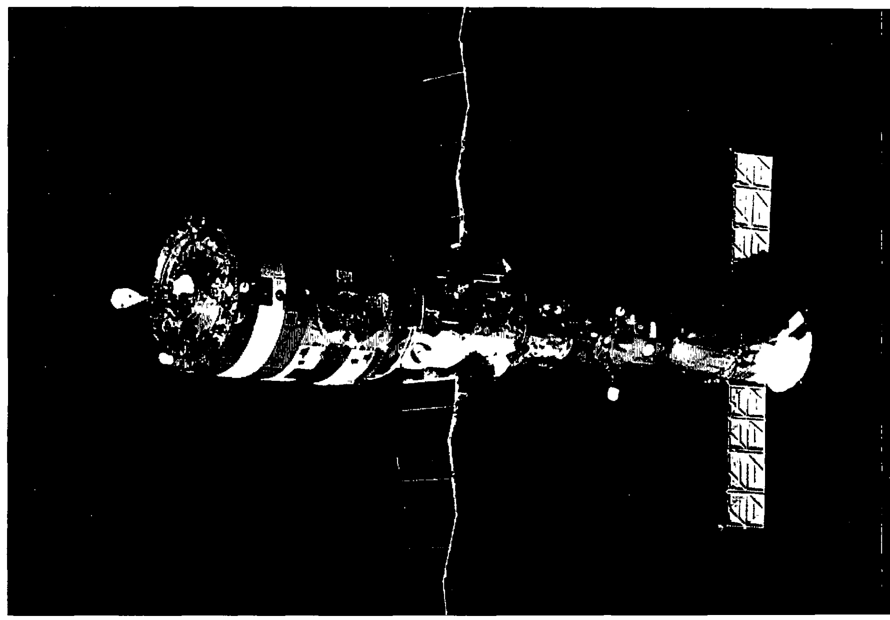
Nippon Electric Company, Mitsubishi Electric, and Toshiba, each a $15 billion plus company and a vertically integrated maker of microelectronics, computers, telecommunications equipment, and other high technology products, previously relied on government contracts and U.S. technology to expand their satellite-related business. Now they are using their own capital and forming partnerships to develop their own products (Davis 1989).

Access: Although only in low Earth orbit, a network of space stations is emerging that will enable live testing of experimental material and technologies, hopefully enabling definitive progress in the critical technology areas blocking our advancement in space. Space Station *Freedom*, a $30 billion, 500-foot U.S. craft consisting of nine pressurized modules and requiring 31 shuttle flights to loft modules, support structures, solar panels, station equipment, and supplies into orbit, will begin assembly in 1995, with completion expected in 1999. Five times the length of the Soviet Mir station, it is a spacecraft, a work station, and an experimental prototype to research products and processes. "It's the first time anything of this magnitude has been attempted by the human race"—Dr. William F. Fisher, astronaut (Broad 1990c). It will house astronauts doing scientific experiments (serving as a research laboratory) and it is currently being regarded as a way station for voyages to the Moon and Mars (serving as a transportation node).

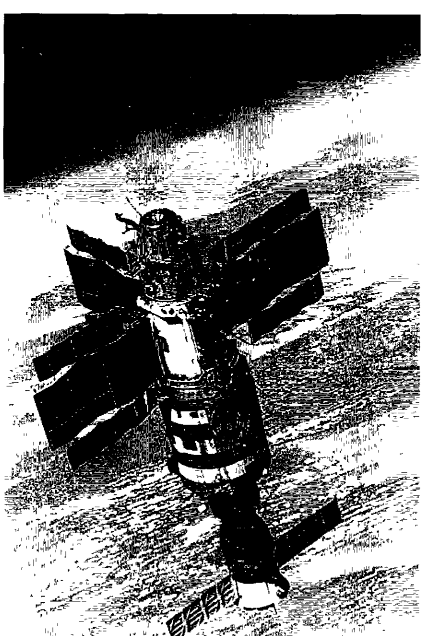
Space Stations



Skylab, launched May 14, 1973; occupied three times during 1973 and 1974; fell back into the atmosphere July 11, 1979

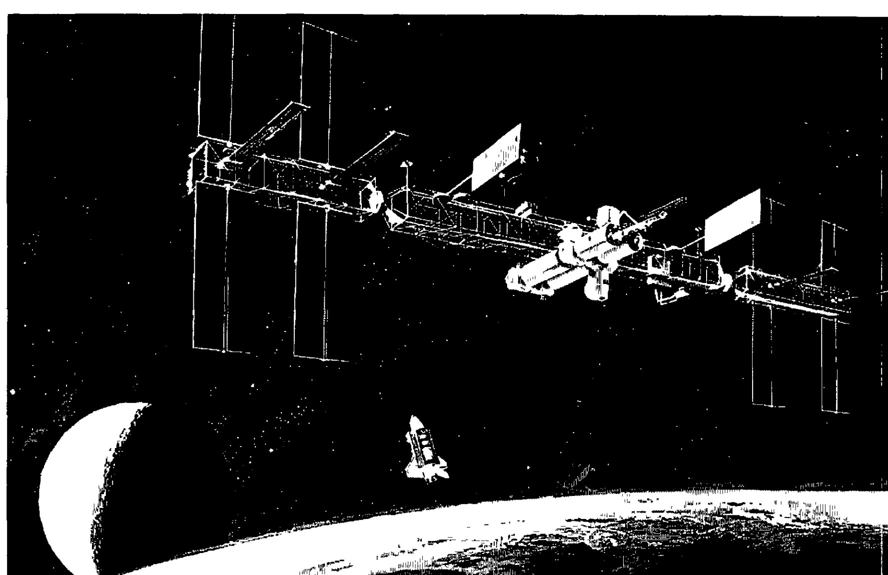


Salyut, with a Soyuz spacecraft docked on its left



Mir, with a Soyuz spacecraft docked below it

Photo: Novosti Press Agency



Freedom

Artist: Vincent di Fate (NASA Art Program Collection)

The near-zero-gravity environment aboard the Space Shuttle and at the space station was expected to lure producers of chemicals, semiconductors, pharmaceuticals, metals, and many other products to sign up or begin negotiating research agreements ("The $30 Billion Potential" 1984). Such basic research interests have not materialized to date. However, as the space industry in general begins to evolve, economic rationale for such basic research might still develop.

The United States has gotten leverage from the Space Shuttle and the space station to date on intergovernmental levels. For example, the Japanese space agency, NASDA, and NASA are sharing the cost of equipment and have agreed to share data obtained from an International Microgravity Lab (IML-1) to be flown on the Space Shuttle *Columbia* in early 1991. The series of cooperative experiments includes developing a new conductive material and investigating potential use of microgravity in making new alloys, semiconductors, and pharmaceutical products not manufactured on Earth (see table 9 for other examples).

The Soviet Mir space station, a 100-foot-long flying laboratory, is nearing completion of the first phase of construction of a 20-ton module (Broad 1990). *Mir* has a readily accessible lab, available on a rental basis to foreign astronauts and scientists as an orbiting factory, observatory, and observation post from which Earth's changing environment can be studied. The Soviets have demonstrated the ability of humans to live and work in orbit for up to 7 months. The Soviets have more in-space experience than any other nation (see table 10); however, their program has some serious coordination problems. The Soviets have underestimated the complexity of the job. On-orbit assembly has been harder than expected. Half of their instruments are not yet operational and have not been fully tested (Broad 1990c). Crews lose time on repairs and technical work, and *Mir* is too small, as it is stuffed with equipment. Nevertheless, of all participants in the space industry, the Soviets share our vision of moving beyond low Earth orbit and have the stature, in terms of in-hand technology, to do so.

TABLE 9. *U.S. Leverage Derived From Infrastructure Development: International Cooperative Efforts*

Project/ launch	Participants	Scope	Leverage for U.S.A.
Int. Micro-gravity Lab (IML-1) Early 1991	NASA, U.S.A. NASDA, Japan	Series of cooperative experiments to develop new conductive material: Investigate potential use of microgravity in making new alloys, semiconductors, & pharmaceutical products not manufactured on Earth	Share cost of equipment, share data obtained
Spacelab sharing	NASA, U.S.A. ESA, Europe Australia Canada Israel (invited by NASA)	Use Spacelab free of charge Non-U.S. provide equipment for	Equipment provided by others, share data obtained experiments
Japanese Satellite Geotail Launch at Kennedy Space Center (1992)	NASDA, Japan NASA, U.S.A.	Largest joint U.S./Japanese space program. 80% Japan, 20% U.S.A. To measure the Sun's energy flow in the Earth's magnetic field	U.S. technology & facilities in exchange for Japanese financing & assembly
Space Station *Freedom* (1995)	NASA, U.S.A. ESA, Europe Canadian Space Agency NASDA, Japan	Build orbiting S.S. *Freedom*	Build larger facility than possible independently, share data

Sources Moosa 1989, NASA 1988

TABLE 10. *Soviet Union Space Development Program: Strengths and Weaknesses*

Areas of strength: in-space experience

- The U.S.S.R. launches 90 to 100 spacecraft yearly, on a regular basis.
- 80% of the active satellites orbiting Earth belong to the U.S.S.R.
- Soviet cosmonauts have flown in space more than twice the hours of American astronauts and hold the record for human endurance in space.
- Space Station *Mir*, while smaller than Space Station *Freedom*, is in orbit already, and occupied. The U.S. space station will be functional in 8-10 years.
- The Soviets launched Energia, a new heavy lift vehicle, in May 1987, a significant technological step. The Energia is capable of launching 100 tons into Earth orbit—4 times the Space Shuttle payload and 5 times the U.S. rocket payload.
- The U.S.S.R. launched 200 payloads into space between 1985 and 1987—10 times the number of the U.S.A.

Areas of weakness: program coordination

- The 1990 mission with the Energia launcher has been cancelled, creating a gap of more than 2 years between heavy lift vehicle flights. It has been rescheduled for 1991.
- The aerospace industry is so decentralized that scientists and other space mission planners are excluded from participation in critical spacecraft development.
- The Soviet 1994 Mars lander-balloon mission is 5 years away from launch but still has not been fully defined.
- Two Phobos Mars missions failed.
- Changes have to be made in the design, software, and quality control of the dominant unmanned segment of the program to overcome the delays and failures of the last 2 years.
- Shuttle development took expertise away from the rest of the program.
- The U.S.S.R. space program employs over one million scientists and engineers, but there has been little substantial output. Risk taking is discouraged; thus, there has been only gradual development of simple systems and a lack of good instrumentation.

Sources: Anderson 1988, Budiansky 1987-88; Covault 1989a, DeAngelo and Borbely 1989; Lavoie 1985, "Soviet Technology," *Aviation Week* 3-20-89.

Access to space does not belong exclusively to national governments and their space agencies. Several private companies have developed space station concepts on their own, including Space Industries, Boeing, and Westinghouse, which are designing a $500 million Industrial Space Facility in Webster, Texas, for completion in the early 1990s, and General Electric, which is designing an unmanned, free-flying minilab.

The Japanese have been rather reticent to date regarding participation in the space industry; however, they initiated a $43 billion space development program for the period 1989-2006, which is composed of a series of commercial projects, including satellite programs, a robotic program, and a space factory for drugs and semiconductors, and infrastructural projects, including the construction of four platforms, an orbital maneuvering vehicle, and an inter-orbit transport space vehicle, as well as participation in the U.S. space station and construction of their own dedicated Japanese space station (by 2008). These projects are in addition to the HOPE spaceplane development project (see table 11). If all of these activities are realized, the Japanese will have a significant base from which to develop products and processes to meet the needs of the space industry as it grows, as well as to create new product concepts for Planet Earth consumers.

TABLE 11. *Japanese Space Commercialization Program, $43 Billion, 1989-2006*

Proposed project	Est. cost, billions of dollars	Timetable
Development of spaceplane "HOPE" (H-2 Orbiting Plane), with H-2 rocket booster	15.86	1989-2006
Participation in U.S. Space Station *Freedom* (space-processing module)	2.23	1987-1995
Polar-orbit platform	1.24	1988-2006
Station common orbiting platform	3.31	1989-2010*
Orbital maneuvering vehicle	0.82	1991-1995
Inter-orbit transport space vehicle	6.21	1992-2000
Geosynchronous orbit platform	2.48	1995-2008*
Manned platform	3.31	1996-2001
Dedicated Japanese station	7.31	2001-2008*
Satellite programs (+ H-2 booster) (incl. communications, broadcasting, weather)	20.5	1989-2004
Robotic space research program	2.4	Early 2000s*
"ADEOS" (Advanced Earth Observation Satellite) (precursor to participation in int. Mission to Planet Earth)	1.2	1994+
Space factory for drugs & semiconductors	No budget yet	Mid-2000s*

*Not included in the $43 billion commercial program.

Sources: Buell 1987; "Japanese Commission," *Aviation Week* 7-13-87.

Destination-Driven Innovation: The Evolution of Major Resource Development Projects

> . . . the empty fragility of even the noblest theorizings as compared with the definitive plenitude of the smallest fact grasped in its total, concrete reality.
> (de Chardin 1972, p. 62)

Colonizing the Moon or Mars seems almost frivolous when placed against the backdrop of problems, concerns, crises near at hand on Planet Earth. However, there are realities taking shape that may make such projects real lifesavers: Our planet is simply exploding with people; our supplies of raw materials and resources are being drained; continued pollution of the environment by manufacturing plants and the burning of fossil fuels is endangering the long-term sustainability of our ecosystem. And the relationships between atmosphere and climate uncovered in the examination of the greenhouse effect on Planet Earth, combined with further examination of existing conditions on Mars, might just reveal to us a methodology for terraforming Mars—delivering to us yet another entire planet to inhabit.

We have a knowledge base developed during the Apollo days that can be readily applied to a return mission to the Moon or to new ventures outward in the solar system to Mars. However, more than 20 years have passed since the landing of Apollo on the Moon, markedly diminishing the pool of experts with hands-on experience. We are fast approaching a point where it will become necessary to reinvent the wheel.

More than the expertise to be lost by not moving toward settlement of a particular destination is the expertise to be gained from the synergy required to plan, develop, and operate such a project. Solar scientists and electrical engineers, for example, tend to keep their own company in planning, designing, and prototyping solar energy systems and equipment. However, when the discussion changes to establishing a colony on the Moon, a whole range of very tangible problems and issues become immediately relevant: dealing with the long days and nights; providing energy for residential, commercial, and manufacturing support; providing sufficient backup to sustain life in the face of any and all calamities. Many insights will come from the interface of prospective corporate users, astronauts, scientists, and engineers.

Finally, the timing of such a magnificently difficult undertaking is critical. The vital capabilities must be in place before site development planning begins. It is simply not possible to begin to design an industrial city that includes technologies that are still being developed. All systems, processes, technologies used must have achieved closure: they must be fully developed, tested, and proven. It is simply not feasible to move workers out to construct a work camp with an unproven power source or oxygen supply. Thus, destination-focused innovation is subsequent to development of the vital technological capabilities, but the destination people can and certainly should have input into the capability development process.

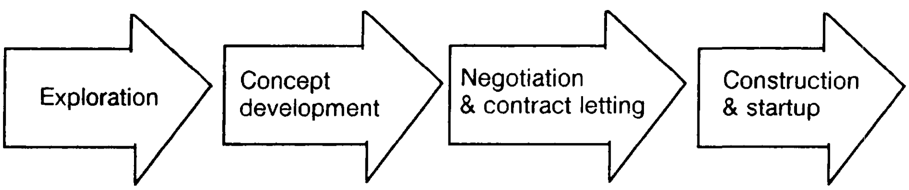
Once exploration of potential sites is completed, a destination is selected, and colonization has been decided on, the major resource development project begins to evolve (see table 12), following a very clear and well-tested path from concept development, through negotiation and contract letting, to construction and finally startup (see table 13), each of which will be examined in one of the following sections.

TABLE 12. *U.S. Mission Scenarios: Destination-Driven Innovation*

Destination	Proposed project(s)	Scope	Est. budget	Est. schedule
Moon (proposed)	As observatory	Sporadic missions to conduct scientific experiments; or unmanned astronomical observatory		
	As base colony (no Mars)	Live off the land, free of logistical support from Earth		
	As milestone to Mars	Manned lunar outpost: Multiple science operations Develop experience Staging area for Mars expedition	$33 billion /year	2019 on Mars
Mars (proposed)	Exploration Technologies R&D	Exploration, operations humans-in-space vehicle technology research to get to Mars at a reasonable cost		
	Mars Rover Sample Return (MRSR)	10 unmanned precursor sampling missions to photograph, return rock & soil samples, meteorological data, water content, mineral composition of soil	$40 billion	10 years
	Mars via Moon	(see Moon)		
	Mars direct	Single expedition	$36 billion /year (peak)	2019
		Manned outpost/ no lunar base		
		Manned outpost prior to lunar base		
	Phobos & Deimos	Moons of Mars		
Universe (under way)	35 missions planned	Extraordinary cosmological discoveries expected that could revolutionize major areas of science, especially physics (unmanned)	$18 billion	1990-95

Sources Broad 1989, 1990a, b, d, Cook 1989, Covault 1988, 1989b, c, d, Del Guidice 1989, Lane 1989, "Mars, the Morning After," *Christian Science Monitor* 7-27-89

TABLE 13. *Life Cycle of a Major Resource Development Project*



Development of a particular destination in space is not free from the need to innovate and advance. We have no experience in establishing large communities that are completely dependent on their infrastructure for oxygen. We have not yet developed construction techniques for connecting materials that will endure in space and provide sufficient protection against radiation. Our entire body of materials, construction techniques, logistical concerns, and supply networks must be experimented with and established. Our notions of project management must be revised—perhaps even to include "breakthrough" management—so that, as the project unfolds, innovative solutions can be sighted, experimented with, and efficiently integrated.

We are not completely in the dark in this regard. All of the very largest scale development projects installed on Earth have had some ground-breaking technology component. In most cases the technology already existed and just needed to be adapted to the expanded scale. Many, however, introduced completely new technology. We may have already zeroed in on the two or three best materials for use in space, but it is another issue altogether to produce enough and work with it in the amounts required to establish an industrial city.

Exploring Uncharted Courses

Before we can reach out to space, master the abundance of its resources, and make it truly ours, we must understand what is there, how it is laid out, and how the various components interact. This requires developing and operating instruments to measure, define, bring back samples, map, photograph, and provide high-resolution imaging.

Unmanned planetary probes have proven to be efficient, exciting, and scientifically rewarding. Voyager 2, for example, was launched 12 years ago and is still functioning flawlessly. In fact, we are the only spacefaring nation that has had the confidence and ability to send machines on long, intricate journeys to the giant outer planets (see fig. 9). This is an exclusive strategic niche in which we have faced little competition to date—perhaps because the payback from such activities is not immediately apparent.

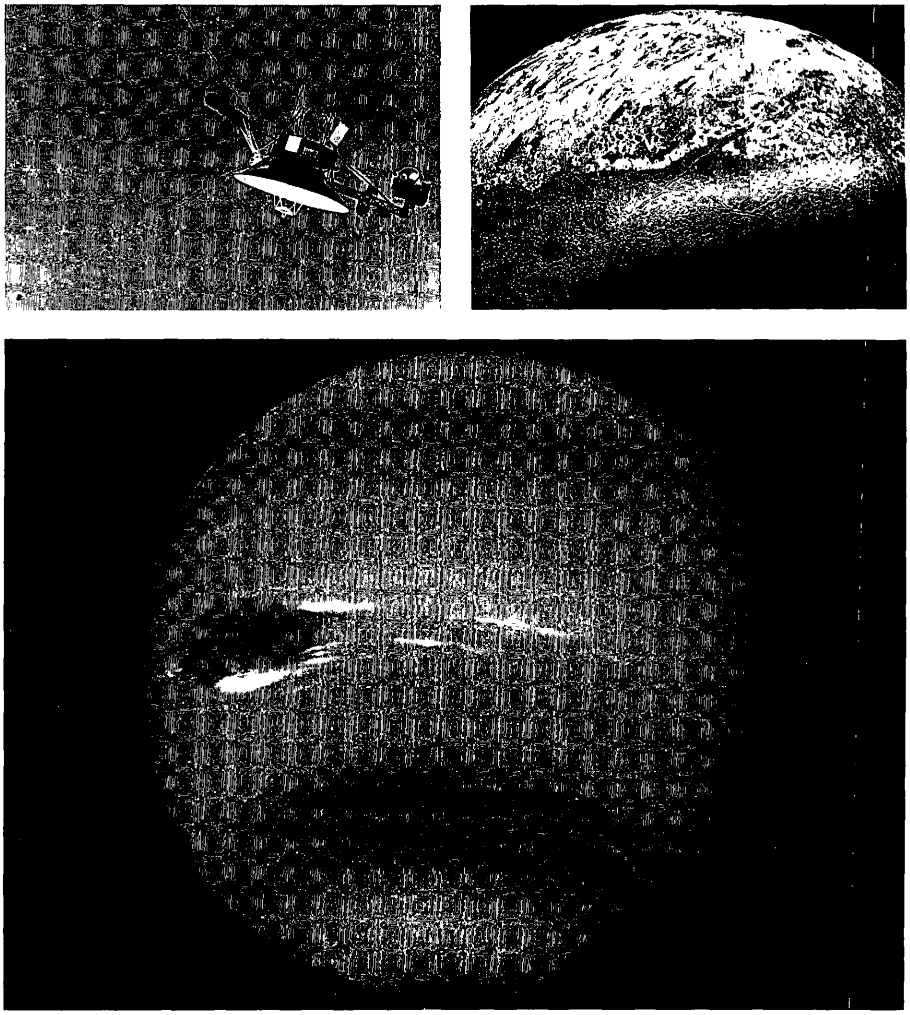


Figure 9

Voyager at Neptune

This Voyager 2 picture of Neptune, taken in August 1989, is one of the best full-disk views of that planet. Neptune, 30 000 miles in diameter, is the smallest of the big gaseous outer planets. The small white features are high clouds of condensed methane, which cast shadows on the top of the denser atmosphere below. The two larger, dark features are the Great Dark Spot and Small Dark Spot. They are the upper expression of giant storms in the atmosphere of Neptune and appear to be similar to the Giant Red Spot on Jupiter.

This view of Triton is a mosaic of a number of close-up photographs taken on August 25, 1989, during the closest encounter of Voyager 2 with the satellite of Neptune. Triton has a complex surface, with a few craters, probably made by comets. Triton probably has a silicate core about 1250 miles in diameter covered by a crust of water ice about 200 miles thick. A thin layer of nitrogen ice may overlay part or all of the water ice. Some of the complex morphology is caused by the fracturing of these icy mantles and the outflowing of liquid water at some time in the past. The temperature at the surface of Triton was measured by Voyager 2 at 38 K, making it one of the coldest surfaces in the solar system. Methane frost is also likely present, and the reddish color of some regions may be caused by sunlight uv radiation reacting with the frozen methane.

A balanced approach is a basic tenet of NASA's current space science strategic plan, which includes a mix of moderate and major missions totaling six launches a year in the early 1990s (Smith 1989). A major new science mission is planned every year through the turn of the century. Over the next 5 years, the United States has a firm schedule to put up 35 scientific flights, a rate 6 times as great as during the past decade and equal to that of the 1960s (Cook 1989).

The task of developing an instrument with which to explore the universe is getting to be a highly collaborative effort. "Big science"—a term coined by Alvin Weinberg in the 1960s when he was director of the Oak Ridge National Laboratory in Tennessee—involves the collaboration of teams of researchers, technicians, Government officials, university administrators, and industrial contractors and large sums of money to produce new instruments to advance our understanding of nature (Lederman 1990) (see table 14, which accompanied a New York *Times* article on the Hubble Space Telescope). The Hubble Space Telescope, the most expensive unmanned scientific spacecraft ever built by the United States and the most difficult to operate, was developed by 60 scientists from 38 institutions selected by NASA and involved nearly every sector of the space agency. A $1.5 billion effort, with an operating budget of $200 million/year, it is a product of such U.S. organizations as the Jet Propulsion Laboratory, which developed the wide-field camera; Lockheed Missiles and Space Company, which built the spacecraft; and Perkin-Elmer Corporation, which devised the electro-optical system. Critical help was also provided by the 13-nation European Space Agency, which provided 15 percent of the funds and supplied some of the equipment in return for an equivalent amount of observing time by its scientists (see table 15) (Wilford 1990a, b).

TABLE 14. *The High Price of Future Scientific Progress*

Federal science projects to be carried out in the 1990's whose construction costs are $100 million or more

Category	Project	Expected Completion	Life	Cost To Build
SPACE SCIENCE				
	**Space Station** An orbiting outpost from which astronauts are to conduct a variety of scientific experiments and possibly set up a forward base for the manned exploration of the Moon and Mars	1999	30 years	$30 billion
BIOLOGY				
	**Human Genome Project** The largest basic biology project ever undertaken, seeking to delineate the entire human genetic code consisting of three billion subunits of DNA that influence human development	2005	--	$3 billion
PLANETARY EXPLORATION				
	**Cassini Saturn Probe** Unmanned craft to examine the giant planet's atmosphere, rings and moons	1996	12 years	$800 million
	Comet Rendezvous and Asteroid Flyby Unmanned craft to rendezvous with comet Kopff for three years of study	1995	12 years	$800 million
	Mars Observer Unmanned craft to orbit planet for observation of surface, atmosphere and gravitational fields	1992	3 years	$500 million
EARTH OBSERVATION				
	**Earth Observation System** Orbiting satellites to obtain wide array of data on environmental changes	2000	15 years	$17 billion
	Upper Atmosphere Research Satellite Satellite to gather data on earth's ozone loss and other chemical trends	1991	3 years	$740 million
	Ocean Topography Experiment Satellite to map ocean circulation and its interaction with atmosphere	1992	3 years	$480 million
ASTROPHYSICS/ASTRONOMY				
	**Advanced X-Ray Astrophysics Laboratory** Satellite to investigate black holes dark matter age of universe	1997	15 years	$1.6 billion
	Extreme Ultraviolet Explorer Satellite to map sky in unusual region of electromagnetic spectrum	1991	2.5 years	$200 million
	Gravitational Wave Observatory Two ground-based instruments to try to detect gravity waves	1995	20 years	$190 million
	8-Meter Optical Telescopes Two ground based instruments for general study of stars and planets	2000	30 years	$170 million
PHYSICS				
	**Superconducting Supercollider** 54 mile instrument to study elementary particles and forces	1999	30 years	$8 billion
	Relativistic Heavy Ion Collider 2.5 mile atom smasher to probe structure of atomic nucleus	1997	20 years	$400 million
	Continuous Electron Beam Accelerator 1 mile instrument to probe same structure in different way	1994	20 years	$265 million
MATERIALS SCIENCE				
	**Advanced Photon Source** Light-generating ring to probe matter's structure	1997	30 years	$455 million
	High Magnetic Field Laboratory Facility for study of magnetic phenomena and materials	1995	30 years	$110 million
	Advanced Light Source Small light generating ring to study atomic structure of matter	1993	20 years	$100 million
TOTAL				**$64.8 BILLION**

Taken from William J Broad, 1990d, "Heavy Costs of Major Projects Pose a Threat to Basic Science," New York *Times*, May 27, sec A, pp 1, 20 The *Times*' sources NASA, Department of Energy, National Science Foundation Illustrations by Seth Feaster

TABLE 15. *The Hubble Space Telescope*

Vision:	Revolutionize mankind's understanding of the universe
Mission:	Determine • How fast the universe is expanding • How old the universe is • What the fate of the universe is
Scope:	Focus on visible and ultraviolet light from all classes of heavenly bodies
Sponsors:	Johns Hopkins University Space Telescope Science Institute NASA
Operation:	Association of Universities for Research in Astronomy, a consortium of 20 institutions
Design/ development:	60 scientists from 38 institutions (selected by NASA)
Equipment development:	• Wide-field camera—Jet Propulsion Laboratory • Faint-object camera—European Space Agency • Spacecraft—Lockheed Missiles and Space Co. • Electro-optical system—Perkin-Elmer Corp. • Glass plates—Corning Glass Works
Development budget:	$1.5 billion, with a final cost of $2.1 billion including $600 million in ground support facilities to test and operate the telescope and process data from it
Operational budget:	$200 million/year
Maintenance:	Serviced by Shuttle astronauts every 2 years; returned to Earth every 5 years for a complete overhaul
Planned observations:	1500 astronomers in 30 countries submitted a total of 600 proposals for observations, in five categories: • Planets in the solar system and search for planetary systems around other stars • Stars and stellar systems • Areas between stars • Galaxies • Quasars

Source. Wilford 1990b

Figure 10

Mars Rover Sample Return

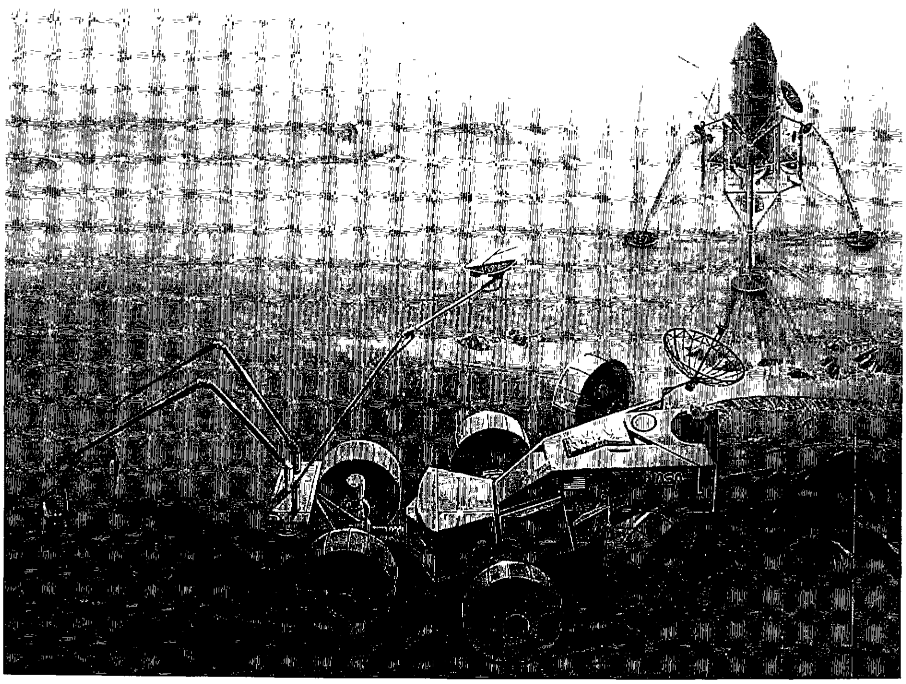
Robotic collection and return to Earth of martian geologic samples would greatly increase our understanding of the history of Mars and would help us make workable plans for human exploration of Mars. Analysis of the samples would help establish how recently volcanoes have been active, what might have happened to an earlier, more Earth-like atmosphere, and whether surface conditions were ever hospitable to living organisms In addition to high scientific value in its own right, such knowledge would enable astronaut crews to focus on the most important locations and scientific issues during their later exploration of the Mars surface.

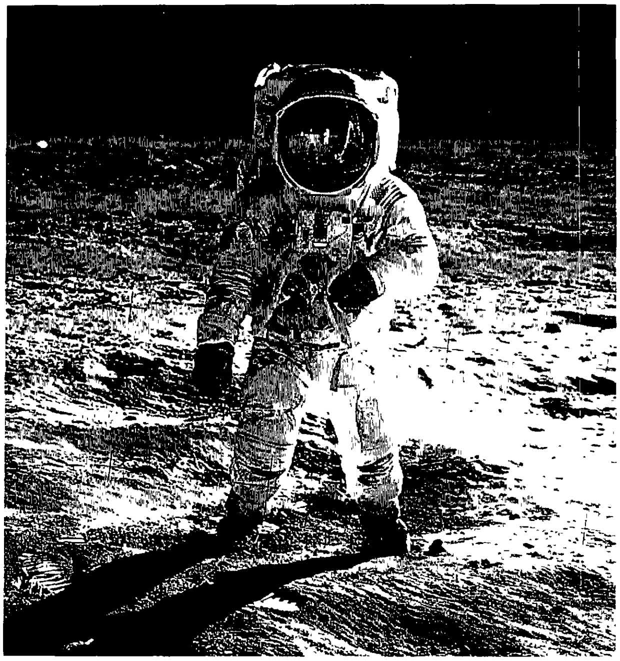
Sample return in advance of human explorers would require either autonomous or remotely operated vehicles that could collect and package samples of rocks, soil, and atmosphere and launch them from the Mars surface to Mars orbit and on to Earth. A roving vehicle (foreground) is one attractive option for collecting the desired samples. Whether the rover moves on wheels (as shown), tracks, or legs, it will have to navigate around surface hazards and deliver the samples to the stationary launch vehicle (background) Current planning suggests that each such rover/launcher combination would be capable of returning about 5 kilograms (11 pounds) of samples to Earth.

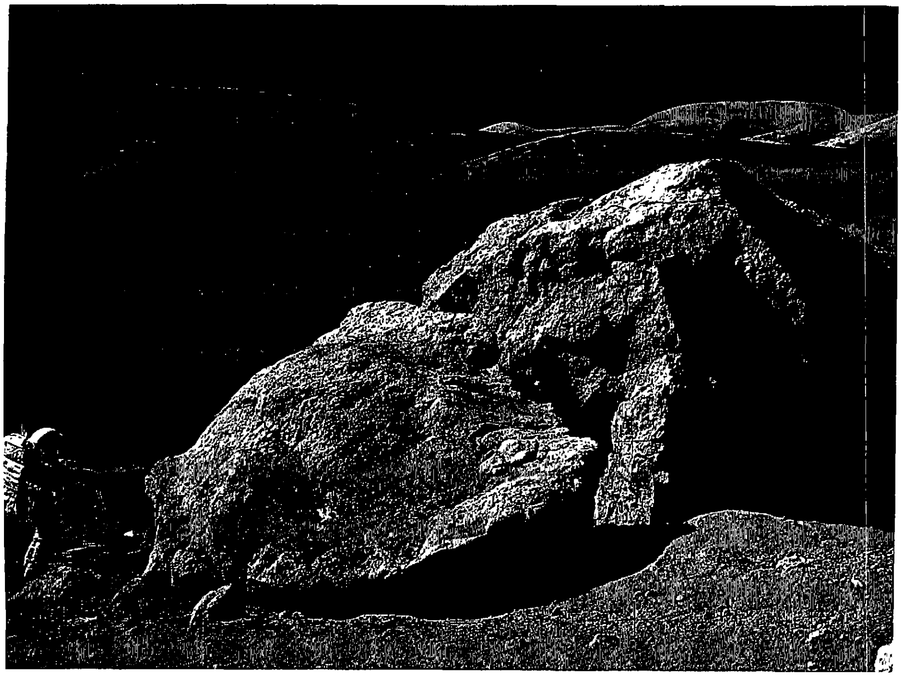
Artist: John Frassanito

Projects such as the proposed Exploration Technologies (formerly Pathfinder) R&D to develop exploration, operations, and piloted space vehicle technology to get to Mars at a reasonable cost and the Mars Rover Sample Return (MRSR), a set of 10 unmanned precursor sampling missions to photograph, return rock and soil samples, and gather meteorological data in order to determine the water and mineral content of the soil (fig. 10) are just some of the exploratory support systems essential to determining whether a particular destination is worth developing.

The two major destinations under serious discussion are Mars (6 to 12 months away) and the Moon (3 days away). Many questions must be answered before a development location is targeted and detailed planning can begin.







Men on the Moon – the First and Last (So Far)

Both Apollo 11 moonwalkers can be seen in the photo above: Edwin "Buzz" Aldrin is the subject of photographer Neil Armstrong, who can be seen reflected in Aldrin's visor. Apollo 17 photographer Gene Cernan was not so lucky when he snapped the photo below, his subject, geologist Harrison "Jack" Schmitt, was concentrating on taking a sample of "House Rock."

The following is one of a series of 5-minute radio programs. Entitled The Engines of Our Ingenuity, *the series is written by mechanical engineer John H. Lienhard and presented by the University of Houston's College of Engineering.*

Mining the Moon

For 20 years, I've wondered why we lost interest in the Moon so quickly after we first walked on it. Maybe it was because we looked over the astronauts' shoulders and saw only a great slag heap. Now geologist Donald Burt asks if it's only that or more. Does the Moon hold riches, or is it just a scabrous wasteland?*

We know a lot about the Moon today. It's rich in aluminum, calcium, iron, titanium, and magnesium. There's also plenty of oxygen on the Moon, but it's all bound up in compounds that are hard to break down. You can get at it, but it'll take a lot of processing. Maybe we can pull some hydrogen and helium-3 out of the rocks as well.

What's absolutely missing on the Moon is anything volatile. There's no water—no loose gas or liquid of any kind. The vacuum on the Moon is more perfect than any we've ever created on Earth.

So can we go after minerals on the Moon? Before we do, let's think about mining and smelting on Earth. We use huge amounts of water—huge amounts of power. We consume oxygen and we put out great clouds of gas. But there is no water on the Moon, nothing to burn, and no power until we put it there.

Without water, the Moon hasn't been shaped the way Earth has, with alluvial strata and deposits. Many of its riches are all mixed together in the surface

(continued)

**Donald M. Burt, 1989, Mining the Moon,* American Scientist, *Nov.-Dec., pp. 574-579.*

For Mars, we need to know: Is there any way to add significant oxygen to the atmosphere and make the planet livable? Was there ever life there? Was there running water? How can the severe temperatures be withstood? Are the moons of Mars similar to our planet's Moon, or different?

For the Moon, we need to know: Does water exist at the poles? Can we manufacture it from lunar resources? What kind of shelter is required to protect against radiation? Should we walk away from development as it is just a heap of stones, or would use of such techniques as a glass enclosure (Biosphere II) allow the re-creation of Earth's atmosphere?

As exploration passes from just a cursory look to indepth analysis of resources available and assessment of feasibility and costs to exploit, the risks and stakes become higher and the need to share risks becomes essential. NASA's role here should be to develop the approaches and techniques for getting to the resource bases and to develop the instruments to measure ore quality. Having done so, the agency should attract resource development companies or entrepreneurs to assume the responsibilities of more detailed risk assessment, extraction, and development.

Developing the Project Concept

Assuming that a location has been identified which provides sufficient resources to reduce or eliminate dependence on supplies from Planet Earth and does not appear to be life-threatening, the next step is to scope out a project concept. This is a critical event requiring enormous thought, as the format decided on can prepare the way for effective cooperation and resourcefulness, or it can establish an arena of intensive competition and friction.

Lunar or martian communities could be company-owned towns (like mining towns in Australia), country-owned towns (similar to the early settlements in the United States), or possibly international towns, the heart of which would be an internationally consistent infrastructure provided by a consortium of participating national space agencies to foster and facilitate residency and participation by entrepreneurs, transient workers, and a full melting pot of Earthlings of all races, nationalities, and backgrounds.

The critical decisions pertain to allocating ownership and project management responsibility among the industrial and infrastructure components of the development project under each scenario.

The company-owned spacetown: A large resource development company (such as an oil extraction and hydrocarbon processing, a metal mining and processing, or a pulp and paper company on Earth) usually decides to set up camp in a remote location because there are resources to be extracted and processed and there is a clear profit advantage to assuming the risks associated with life in a forbidding environment. If the location is far from civilization, the resource development company takes responsibility not just to supply the tools, techniques, processes, and people to perform the profit-generating task but also to provide the life support components usually supplied by governmental agencies in more civilized areas—such as water, food, electricity, transportation vehicles and networks, education, and health care.

From our experience with company towns on Earth, it is clear that they are homogeneous (even if the project sponsors are joint-venture partners—everyone is working in the same place). Problems faced by resource developers responsible for establishing a company town are monumental, encompassing issues far beyond business management and profit generation. Besides the logistical problems common to all such mega-scale undertakings, there is the problem of transplanting a complete communal system. The isolation, the feelings of hardship, and the social conflicts of workers operating under such stressful conditions add dimensions to the management task that are perhaps the most complex. It appears that technologically we are capable of bringing enormous resources to bear on a problem. Risks and exposure can be reduced to tolerable levels via joint ventures and multicompany consortia. We have expertise in managing in remote locations and marshaling the very best talent for a particular task. The real block to smooth performance has proven to be the human element. Planners frequently overlook the environmental, social, and political issues involved in creating a company town here on Earth—an oversight which may, in fact, account for the most costly budget overruns and schedule delays.

It should be noted that the cost of these large infrastructure components raises the break-even point of the project, thereby requiring that the productive output be raised. Infrastructure development also increases project complexity, as responsibilities that usually belong to local governments fall to the project sponsors. And the more complex the project, the more difficult and dangerous the management and coordination task.

Mining the Moon *(concluded)*

layer of dust. We'll probably begin by surface mining for oxygen to sustain our outposts in space. Metals will be useful byproducts.

Pollution would be a terrible problem if we mined the Moon the way we do Earth. The Moon's near-perfect vacuum is going to be useful in all kinds of processing. If we dumped gases on the Moon, the way we do on Earth, we'd ruin that perfection.

You see, most gas molecules move more slowly than the lunar escape velocity. Only the fastest ones get away. Now and then, slower ones are sped up as they collide with each other. Then they also can escape. Over the years, the Moon loses any gas released on its surface, but not right away. So we have to invent completely closed processes to take the Moon's wealth. That way we'll protect one of the Moon's greatest resources—its perfect vacuum.

The Moon is a rich place, but we must put our minds in a wholly different space to claim its riches. The Moon will reclaim our interest as we learn to see more than a slag heap. The Moon has held our imagination for millennia, but in a different way each time our knowledge of it has changed. Today, our vision of the Moon is on the threshold of changing yet again—as we learn to look at it with a process engineer's eyes.

The country-owned spacetown: We could go to the Moon or Mars, plant our flag, and plot out our territory (though we cannot *claim* the territory; see Goldman's paper on international law) much as the early settlers did in America in the 1600s. We would create a rapport within the town but might recreate the conflict and friction between towns owned by different countries which has occurred on Earth.

The governmental body, possibly NASA, would have an important role to play: There are certain facilities which are funded, installed, and managed by governmental authorities in communities around the world; these include power, transportation systems, water and waste treatment systems, and medical, educational, athletic, and other such facilities that promote the general well-being of the population. The scope of space infrastructure will certainly be larger than the King Abdulaziz International Airport in Saudi Arabia (fig. 11), the largest airport in the world, which was built in the middle of the desert at a cost of $4.5 billion by 10 000 workers (at the peak of construction). It is a self-contained city that includes a desalination plant to get drinking water out of sea water, a hospital, and its own telephone system. It was constructed to provide adequate shelter, eating facilities, and restroom accommodations for 80 000 travelers expected during the 36-hour period of the hajj, the annual Muslim pilgrimage to Mecca.

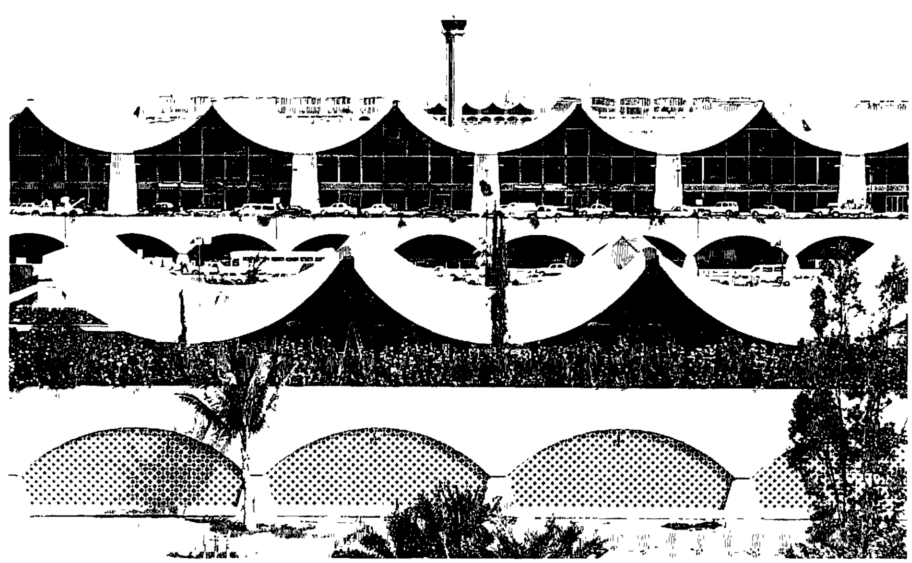


Figure 11

South Terminal of the King Abdulaziz International Airport in Saudi Arabia

Courtesy of the Information Office of the Royal Embassy of Saudi Arabia

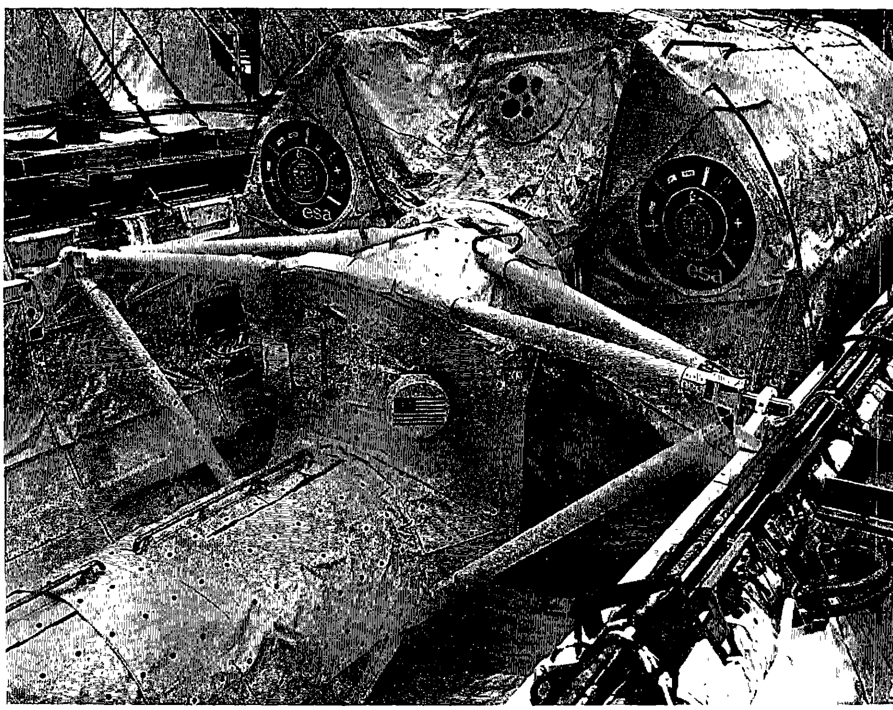
The advantage of governmental development and management of supporting infrastructure is that it provides access to life-sustaining facilities to small as well as large enterprises and to individuals of all economic levels, enabling them to undertake entrepreneurial as well as corporate economic activities.

Governmental involvement in these sectors encourages the most broad-based development scenario. Since these projects do not necessarily generate a profit, the go/no-go decision is typically based on cost/benefit analysis: How many people will be serviced by a particular infrastructure facility and how much economic activity can be stimulated in return for the costs assumed? Government initiation is not intended to create a welfare state but rather to foster economic activity, support diversified growth, and above all create taxpayers who will pay off the debt incurred in establishing the infrastructure, cover its operating costs, and support infrastructure expansion. NASA could seed the growth of the initial community and then sell the infrastructure to the community, once a sufficient economic base was created.

The international spacetown: The opportunity exists to go beyond community development as we know it today and establish a true international—or citizen of Planet Earth—community. A consortium of national space agencies could jointly plan, design, and install an infrastructure network to support a broad diversity of economic activity in space. Technical, financial, and market supply and demand benefits could be derived from this global cooperative effort. It is essential that technological compatibility and interchangeability be achieved so that products and processes will be transferable to and usable by all. Standards for gravity, oxygen, food quality, screw sizes, shielding densities, and maintenance requirements need to be set. Space medical standards and practices must be established. The costs of setting up life in such remote locations will be enormous. It will be wise to share fully the costs of infrastructure development, undertaken in cooperation. Again, the goal is to create a community of economically productive taxpayers, who will begin to reimburse the national space agencies for their design and development efforts (funds which could then be used to move to a subsequent planet and begin the same seeding process).

The ultimate objective of the international spacetown, however, is to create a thriving self-governing metropolis that is democratic and full of opportunity for individual entrepreneurs as well as large, established global corporations.

In an environment where there probably will not be curtains at the windows and paintings on the walls for some time, it is important that individual creativity and ingenuity be highly respected and given broad leeway to realize itself.



Spacelab 1, an Example of International Development of Space Infrastructure

Negotiating Risk Allocation

At the very largest, megaproject scale of development, no single organization has yet been able to finance, provide the technology for, or market the output of the completed facilities alone. A broad array of technologies, both infrastructural and industrial, are required in large volumes to attain mega-scale project parameters. In addition, abundant transfers of proven technological processes and secured market demand for the output are required to attain economic feasibility. The project requirements define the extent and nature of the inter-organizational collaborations needed to bring the project to fruition. See table 16.

TABLE 16. *Project Requirements and Consortia Formation*

		Requirements and consortia contract types		
Type of project	Project requirements	Capital sourcing	Technology transfer	Market access
Resource development project	Technology transfer Capital sourcing Market access	High risk	Custom-tailored	Critical to economic viability
		• Equity • Loan and repayment in output • Suppliers' credits	• Construction management • Design/construct • Consortium of contractors	• Buyers' consortium • Production sharing • Long-term purchase agreements • Coproduction (or barter or payment in kind)
Turnkey manufacturing facility	TT CS MA	Low risk	Off-the-shelf	Not critical
		• Suppliers' credits tied to turnkey contract • Possibly some equity, but not necessary	• Turnkey contract • Turnkey contractor's consortium	
Infrastructure development project	TT CS	Low-high risk (depending on type)	Generally custom-tailored	Cost/benefit calculation
		• Concessionary financing • Equity usually held by governmental ministries	• Construction management • Design/construct • Consortium of contractors	

Commercial resource development projects are undertaken because of a clearly visible opportunity to make a profit in the face of clearly high risks. The extraction and processing of fuels and minerals, and in certain cases the harnessing of power sources, come under this heading. In the developing world, these projects are usually sponsored by publicly owned corporations or state-owned enterprises and depend on private equity capital in addition to any public loans or grants the project might be eligible for. Overruns and delays during project implementation can as frequently be attributed to the partners selected (too many, in conflict, different goals for the project) as to logistical and other difficulties intrinsic to the project itself.

Some commercial projects are "turnkey" projects, in which a factory can literally be transplanted to the site. These might be manufacturing facilities, hydroponic food farms, and other types of processing plants that are self-contained—perhaps even a factory to extract liquid oxygen from regolith on the Moon (fig. 12). Turnkey projects are lower risk and are typically supported by export financing from the home country of the technology process owner, in addition to equity capital provided by the plant owners.

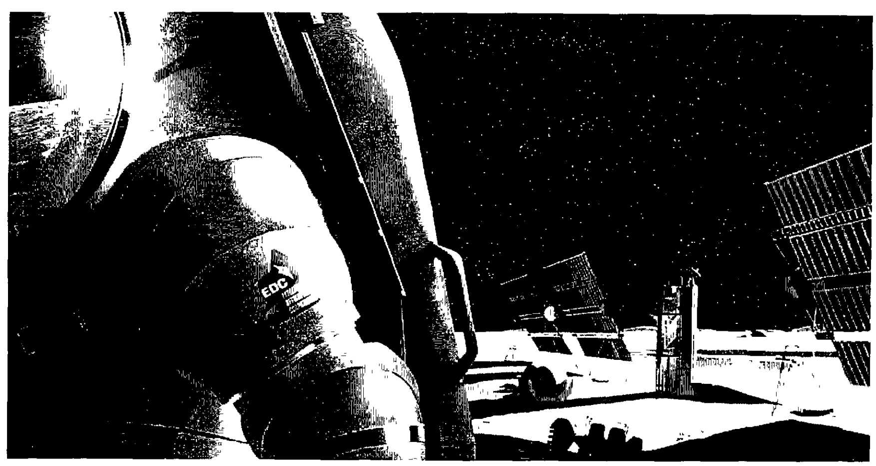


Figure 12

A Turnkey Factory on the Moon

Development of lunar resources may turn out to be a commercial enterprise. In this artist's illustration, a fictitious company, the Extraterrestrial Development Corporation (EDC), has installed an oxygen plant on the lunar surface and is operating it and selling the oxygen produced to NASA and possibly other customers. The fluidized bed reactor in the background uses ilmenite concentrated from lunar soil as feedstock. Oxygen is extracted from this ilmenite by hot hydrogen gas, making water vapor. The water is electrolyzed, the oxygen is captured and stored as a cryogenic liquid, and the hydrogen is recycled back into the reactor. The power for the plant comes from the large solar collectors on either side of the reactor

Artist: Mark Dowman

The final class of projects is infrastructure development projects, which provide life-sustaining needs to a community, enabling its members to carry out productive, wealth-generating activities. Such a project is often owned and operated by a governmental agency and, once operational, supported by taxes and user fees. The initial installation of these infrastructural facilities, such as water supply, waste treatment, power supply, public housing, sports and recreational facilities, as well as transportation and communication networks and public administration buildings, is typically financed by loans provided by international development agencies or capital raised from the public in the form of bonds. A core infrastructural network can be established at the start of human settlement on other planets and expanded as the human base it supports is extended.

In my experience of megaprojects developed on Planet Earth, in particular in remote locations in developing countries (Murphy 1983), I have seen effective multicompany efforts to stabilize the project parameters through consortia negotiation and inter-organizational contracting.

What a consortium is: In general, as the level of risk increases, so does the likelihood that a consortium of companies will be formed to insulate any one participant from potentially devastating financial consequences, should the project fail. I am consciously substituting the term "consortium" for the expression "joint venture," because it suggests a more pragmatic basis for collaboration and for sharing risks, negotiating responsibilities, and determining the split of profits, if the project succeeds. The parties involved in a consortium contract among themselves to specify the responsibilities of each. The common features of a consortium are that

- It is task-based. Participants are selected on the basis of which project requirements (capital sourcing, technology transfer, or market access) they are capable of satisfying, rather than on who they are or how large their organization is.
- It involves risk-sharing. All members assume some measure of risk. Each member's reward is tied to the level of risk assumed, with the payback period being clearly delimited.
- There is some competitive advantage. Typically, a member is selected because it can offer to the combination of participants one or more competitive advantages.

The decision to form a resource consortium appears to be more related to the level of project risk than to the level of sophistication of the capabilities of the players involved, as these collaborative arrangements can be found throughout the developing world in all industry sectors and have involved most of the leading organizations of the world.

How project needs are met: These collaborative undertakings provide an effective way to satisfy the enormous capital sourcing, technology transfer, and market access requirements common to all megaprojects by ensuring that the critical drivers of economic viability are satisfied. However, the contributions of such consortia to enhanced effectiveness may vary by industry sector:

- For metal mining projects, consortia make it possible to increase the scale of a project beyond the financial abilities of a single company in order to cover infrastructure development costs (sometimes up to 60 percent of total investment) and meet economic criteria. These requirements have been more intense of late, as most of the Earth's remaining metal reserves are in relatively inaccessible locations.

- For metal and petrochemical processing projects, consortia enable companies to eliminate the threat of price fluctuations on the output by establishing long-term purchase agreements with buyers, while at the same time hedging their risks over several projects by taking a low equity share in each.

- For liquefied natural gas (LNG) projects, consortia are formed to establish a long-term purchase agreement with a guaranteed buyer who must also build a tailormade receiving terminal to unload the output. Unless this crucial requirement is met, the construction of the production facility—typically ranging from 500 million to several billion dollars—cannot be justified.

- Oil refineries, by comparison, seem to have little problem in finding buyers for their products; thus, the need to form a consortium to build one has been less common.

Not only does the resource consortium provide an important vehicle for controlling some of the external risks of a project which are beyond the sponsor's ability to manage alone, but also, depending on the expertise of the partners, the consortium may bring together sponsors whose technology and managerial assistance can enhance control of the internal risk factors of the megaproject at the same time. On the other hand, if managerial expertise is lacking, contracts for project or construction management can be established with organizations skilled in the weak areas.

How participant risks are minimized: Capital funding and market access are often secured for the project through multi-organization consortia, involving a share of the project equity while minimizing risk exposure for the respective participants:

- A multinational resource development consortium is typically composed of shareholder corporations from many countries, each holding a very low percentage of equity, combined with long-term purchase agreements for access to the raw materials output by the project. By taking a low equity interest in the project, each corporation is able to syndicate its investment risks over a large number of projects and thereby stabilize its raw material supplies.
- A national resource development consortium is composed entirely of companies from the same country; it is composed of all companies in a particular industry at a very low equity share per company, with a substantial portion of the capital loaned to the project by agencies of their government. The net effect of such a consortium is to equalize the risks and stabilize supply sources, as well as the cost of those raw materials, across an entire industry within a country. Thus, a country like Japan, which depends on imports for 90 percent of its raw materials, can marshal industry-wide support for any raw material acquisition the national government would like to make. Furthermore, it shifts competition between companies from obtaining the best price for raw materials to such downstream advantages as more efficient processing or manufacturing facilities and more focused marketing or distribution networks.

It is becoming easier to put together consortia, as the key players have built up an experience base with respect to inter-organizational collaboration. As industries have evolved over the last two decades, the ground rules for collaboration among international developers have changed from nationalistic to global strategic perspectives and dimensions. Joint technology and marketing ventures among companies that have traditionally been competitors have become common.

Managing Project Construction and Startup

As complex as construction and startup are in the most remote of locations on Earth, they will be orders of magnitude more complex on another planet. If handtools or screws are forgotten, it will be a long way back to get them; replacement parts will not be an airplane ride away; and Federal Express or UPS will probably not have offices in the closest city.

Several decisions can affect how roughly or smoothly the construction and startup will go.

Integrated or phased: Megaprojects, whether resource or infrastructure development, are brought to fruition under management scenarios that best meet the needs of the participants, the capital constraints, the level of technology in hand, and the demand for the output. Projects can be developed in an integrated manner, installing all components at the same time. An example is the $20 billion Al Jubail Industrial Complex in Saudi Arabia (fig. 13). Expected to take 20 years

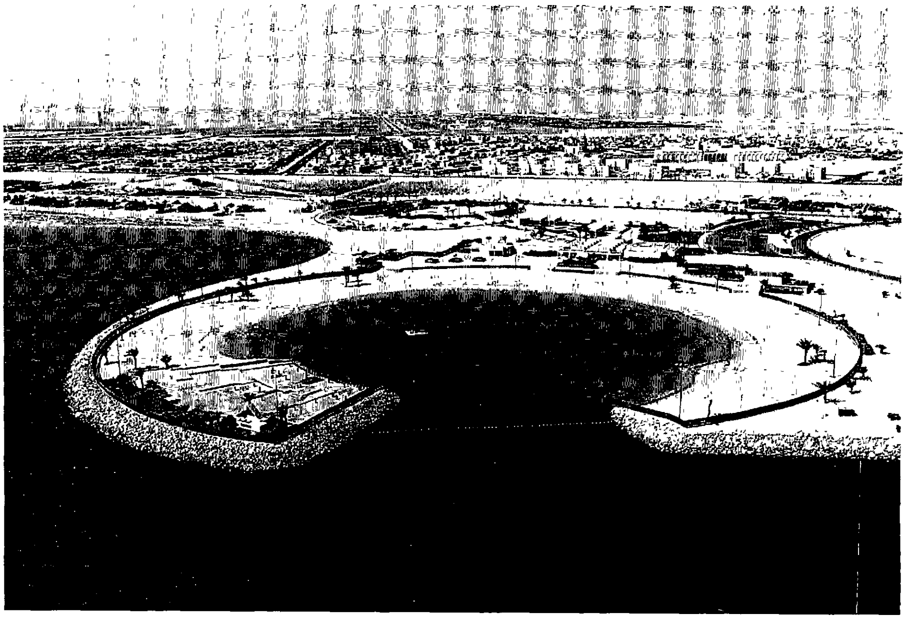


Figure13

Seaport of Al Jubail Industrial Complex in Saudi Arabia

Courtesy of the Information Office of the Royal Embassy of Saudi Arabia to develop, with a completion date set for 1997, it includes three petrochemical plants, an oil refinery, steel and aluminum plants, water and waste treatment facilities, a desalination plant, housing, a training center, a seaport, and an international airport—all of which were planned and developed under one, integrated project concept.

Projects can also be developed in a phased manner. One facility can be installed which then provides the base from which additional facilities can be built. An example is the development of the Bintula area in Malaysia. First a $5 billion liquid natural gas facility was installed, supported by a basic work camp and infrastructure. A subsequent project is being planned to develop the entire area as a resort, including a new city, at a cost of $10-15 billion.

Each approach has benefits and risks, which are summarized in table 17. An integrated approach puts stress on the internal aspects of the project, making procurement, logistics, and labor management more complex. However, there are external advantages to coming onstream earlier, such as a shorter period for borrowing capital and a quicker payback.

Phased development stretches out the completion date of the fully integrated project, thus allowing competitive inroads, but permits greater control over each section. Procurement is phased, there are fewer players involved at one time, and adjustments are smoother.

TABLE 17. *Economics and Project Sequencing*

Approach	Risks	Benefits
Integrated development	Overload (internal) • More complex • More procurement, logistics problems • Labor management • Cultural conflicts	Online sooner (external) • Shorter demand for capital • Quicker return
Phased development	Competitive threats/ inroads (external) • Competitive moves • Inflation in cost • Other variances in demand estimates	Able to test out one step before moving on to another (internal) • Simpler • Phased procurement • Fewer players at one time • Smoother adjustments and interface

For NASA, the issue is whether it is better to develop a work camp on the Moon only, or on the Moon and on Mars, or on the Moon first and then on Mars. Should a small outpost be developed, or an entire community? What functions will the base serve? Is it an observation post from which to conduct science, or is it a resource development base for mineral extraction, or is it an infrastructure base from which to explore and experiment in search of wealth-generating activities? The ability to answer these questions will be determined by the findings from various exploratory missions. The ability to respond to those findings will depend on the extent of technological breakthrough achieved in our capabilities.

Achieving synergy: The most important opportunity for capitalizing on cost-reduction opportunities, not to mention actively preventing overruns, lies in maximizing efficiencies during the construction phase; that is, the period during which most of the capital is spent. The ability to recognize and take immediate advantage of the tradeoffs that must be made daily can provide significant cost savings. Megaprojects often entail several kinds of construction by multiple contractors simultaneously; therefore managerial synergy is critical: (1) from one stage to another, (2) among processes installed, and (3) between the goals of the sponsors and the services of the technology providers. Attention must be paid as much to the transition points of a megaproject as to performance within each component. Unbudgeted costs have often been incurred at these critical transition points, where leadership responsibility has not been clearly defined.

Unique megaproject management expertise: Companies which have been successful providers of project management expertise in the developing world have relied on their strong reputations and expertise from their home countries as their entree into the megaproject arena. Since companies are not awarded contracts to experiment with or diversify their services but rather to deliver proven expertise, U.S. firms have been the companies of choice because of their track record of fully implemented mega-scale projects that have been developed at home. All projects of $1 billion or more in the developing world requiring project management capabilities (such as oil refineries, gas processing facilities, and transportation infrastructure) have been awarded exclusively to U.S. design/construction firms.

The most complex megaprojects have been designed, engineered, constructed, and managed by the U.S. design/constructors Bechtel, Fluor, and Ralph M. Parsons. These three companies are superior in their ability to deal with complexity through sophisticated project management systems and worldwide procurement networks. This suggests that NASA's continued attention to megaproject management innovation will ensure that this U.S. tradition of being the preeminent providers of complex project management services worldwide—a critical national competitive advantage—will be sustained.

The consortium is also a common approach used by small or medium-sized design, engineering, construction, or manufacturing companies to achieve the scale required to bid on one of these jobs. Consortia and independent turnkey contracts are generally written on a fixed-fee basis, with the contractor absorbing most of the risks associated with delays or overruns. There are numerous variables that go into determining the optimum contractual formula. In general, the purpose of these packages is to take risk away from the sponsors, while at the same time removing day-to-day managerial control of construction from the sponsor.

Options for a project sponsor: The project sponsor's objective is to establish an organizational framework that lets each participant know what to expect from the others; how to handle changes in cost, schedule, or tradeoff opportunities; how to reach decisions; how to keep the project moving. An effective network of project intelligence and a spirit of "mega-cooperation" must be achieved. Decision-making must be done swiftly and surely, giving prime consideration to the status of the project rather than to the status of the person who sits across the table.

A review of existing megaprojects indicates that there are three generic ways in which owners or sponsors structure their projects. A sponsor's level of involvement is a function of that firm's in-house project management competence. A sponsor can

- Actively manage. Manage the project directly—either as an independent owner or as a partner in a joint venture.

- Direct and control. Contract out the project preparation to consulting engineers and the construction work to contractors or both, maintaining responsibility for day-to-day coordination and management.

- Review and approve. Contract out the complete job to a project manager, a turnkey contractor, or a contractors' consortium. Project management contracts are usually cost plus, while turnkey projects (which delegate managerial or supervisory control to the contractor) are fixed fee, thereby transferring risk to the contractor. In this case, a large contingency fee is commonly added to the price to cover potential risks.

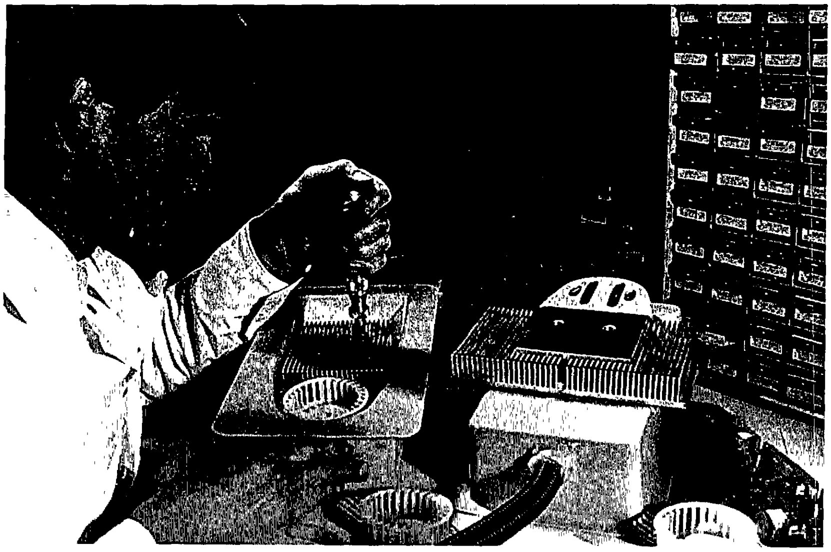
As NASA gets closer to launching the most complex megaprojects of all time, it is important to recognize that sufficient capital, technology, and market access can be pooled from a global network of corporations and financial institutions without compromising NASA's role as the energizing leader with the ennobling vision.

Section 3: Sourcing—and Sustaining—Optimum Financing

> Thanks to our discoveries and our methods of research, something of enormous import has been born in the universe, something, I am convinced, will never be stopped. But while we exhaust research and profit from it, with . . . what paltry means, what disorderly methods, do we still today pursue our research.
> (de Chardin 1972, p. 137)

In words President George Bush quoted from a news magazine, the Apollo Program was "the best return on investment since Leonardo da Vinci bought himself a sketchpad" (Chandler 1989).

Admiral Richard Truly, NASA Administrator, concurs. He believes that no space program on Earth today has the kind of technology and capability that ours does. Our space program is an integral part of American education, our competitiveness, and the growth of U.S. technology. Compared with other forms of investment, the return is outstanding: A payback of $7 or 8 for every $1 invested over a period of a decade or so has been calculated for the Apollo Program, which at its peak accounted for a mere 4 percent of the Federal budget. It has been further estimated that, because of the potential for technology transfer and spinoff industries, every $1 spent on basic research in space today will generate $40 worth of economic growth on Earth.



Spinoffs

Spinoffs from NASA's development of space technology not only provide products and services to the society but also are a significant boon to the American economy. Among the hundreds of examples are this sensor for measuring the power of a karate kick and this thermoelectric assembly for a compact refrigerator that can deliver precise temperatures with very low power input. Estimates of the return on investment in the space program range from $7 for every $1 spent on the Apollo Program to $40 for every $1 spent on space development today.

The critical factor driving productivity growth is technology. The percentage of our national income that we invest in research and development is similar to the percentages invested by Europe and Japan; however, since our economy is so much bigger, the absolute level of our research and development effort, measured in purchasing power or scientific personnel, is far greater than Europe's or Japan's (Passell 1990). But our ability to sustain an appropriate level of investment in R&D is being threatened. We are overwhelmed by our national debt, our decaying infrastructure, and the savings and loan bailout, which alone is expected to cost the Government $300-500 billion, possibly more. To pay these debts would cost each and every American taxpayer between $1000 and $5000, and this is a payment that will not enhance national security, promote economic growth, or improve public welfare (Rosenbaum 1990). This obligation is orders of magnitude greater than the commitments U.S. citizens have made to their space program.

TABLE 18. *Expenditures per Year by U.S. Citizens, Selected Examples*

Expenditure item	Amount per capita
Space station funding, 1990 budget	$23.68
Entire space program, 1990 budget	$55 (approx.)
Apollo Program at peak	$70.00 (1988 dollars)
Beer	$109.00
Legal gambling	$800.00

Source Sawyer 1989

We have a military budget of $300 billion (compared to $200 billion per year spent on legal gambling), yet we are too broke to do anything (Baker 1990). Further, our return on investment in research and development is not as effective as it once was. It is possible that military spending is draining critical research efforts; it may be that the American emphasis on basic research has freed Japanese scientists to skip the gritty groundwork and focus on commercial applications; or is it that American corporations may not be good at turning research and development into marketable products? (Passell 1990).

Half of all Federal tax dollars go to the Pentagon. These large expenditures have hurt the competitive position of the United States and have kept the level of investment in the civilian economy, as a share of gross national product, lower than in Europe or Japan. For example, in 1983, for every $100 we spent on civilian capital formation, including new factories, machines, and tools, we spent another $40 on the military. In West Germany, for every $100 spent on civilian investment, the military received only an additional $13. And in Japan, for every $100 spent on civilian investment, a mere $3 was spent on the military. Military spending is 6 percent of GNP, but it pays for the services of 25 to 30 percent of all of our nation's engineers and scientists and accounts for 70 percent of all Federal research and development money, $41 billion in 1988 (Melman 1989).

A "peace dividend" is in prospect, if Congress will cut military spending. A peace dividend offers an opportunity for a political leader to capture attention and resources and do great good. The total dividend through the year 2000 could be as much as $351.4 billion (Zelnick 1990). How the peace dividend should be spent calls into play one's values. Many alternatives are mentioned (the savings and loan bailout, for instance), but NASA is never mentioned as an option.

Under this scenario of declining technological edge, constrained financial resources, and a budgeting process that subjects approved financing to annual revisions and potential cuts, how can NASA adequately source—and sustain—optimum financing?

- Potential sources of funds
- Opportunities for sustainable collaboration
- Life cycle of NASA's funding responsibility

Potential Sources of Funds

The traditional source of financing for any nation's space program is government financing of the national space agency. But government financing alone has proven to be inconsistent and unreliable in the long term, as the space program is forced to compete with other national priorities. Furthermore, as the scale and scope of space projects increase, it becomes beyond the capabilities of a single national government to assume the risks alone—it is effectively wagering national wealth on projects of varying levels of risk.

The stakeholders in the various space development activities can and increasingly should be called upon to participate in the financial risks and enormous potential rewards of innovation that is driven by the "consumers" of Planet Earth, our need for advanced technological capabilities, and our desire to develop livable destinations in space. These stakeholders include

- *The national space agencies* of leading industrialized (and some other) countries around the world typically have a space exploration and development budget representing about 1-6 percent of their GNP.
- *Major corporations and minor entrepreneurial companies* have a new product or process development budget or an exploration budget that is allocated for high-risk, wealth-creating innovative activities.
- *Private investors,* whether individuals or pension funds, have a portion of their savings portfolio dedicated to high-risk, potentially high-return investments in stocks—and even some bonds (i.e., junk).
- *The users of catastrophic pollution-causing products or processes* are recklessly risking the health of our planet in our lifetime—and we are not sure that the damage is reversible. Such reckless users could be assessed a pollution surcharge to fund breakthrough research on nonpolluting new product and processing technologies.
- *National/state/city infrastructure agencies and international development agencies* receive funding to provide particular life support basics, such as water, power, waste disposal, and schools, to their communities or developing nations. A well-honed, functional infrastructure maximizes

productivity, enabling the creation of wealth by its residents. Elimination of overlap of effort and global coordination could free up massive amounts of investment money to achieve more effective results.

If these capital reserves were added up per stakeholder category, sources of funds for Planet Earth problem-solving and space development could readily be uncovered in abundance.

Opportunities for Sustainable Collaboration

Examining how these capital resources are allocated, we can readily see that there are billions of dollars being invested in research, design, development, and improvement efforts which overlap and duplicate each other among organizations in the United States, as well as around the world. Many efforts fail to achieve any significant technological advancement precisely because funds are not adequate or scope of authority is not sufficient to make any significant change. For example, if it were decided that automobiles were too heavy, causing the serious deterioration of our nation's infrastructure, and that our automobiles and roadways should be redesigned to achieve a major technological advancement, such an agenda could not be decided on by General Motors alone or the U.S. Department of Transportation alone. Technological advancements of such scale, and more importantly of such global significance, need to be mounted under leadership so engaging and with a vision so encompassing as to ensure that all the key players involved make their capital resources, technological expertise, and access to market demand available to the project.

To take the discussion of our transportation networks one step further, the facts make it clear that the need for technological innovation is not hypothetical but quite real:

- Our national transportation infrastructure has gravely deteriorated, requiring \$3-5 trillion to reconstruct.
- Our auto industry has lost its competitiveness—at home and abroad, and we are struggling to regain a reputation for quality that remains elusive.

- The outlook for transportation vehicles' being able to move about our cities and suburbs at the local speed limit is dimming, as roads are becoming increasingly clogged and overburdened. Such approaches as computerized traffic control screens within vehicles are being tested.

- The carbon monoxide released from combustion engines in autos and their petroleum-based fuels is presenting a grave hazard to the global ecosphere.

- And numerous projects are on the drawing boards around the world to break through our current propulsion barriers, preparing the way to travel at higher rates of speed.

The key players responsible for shepherding such events include the national, state, and city transportation agencies, auto manufacturers, oil production and retail companies, propulsion-focused R&D groups, and automobile buyers and drivers. Their diversity of interest and scope of responsibility and the lack of a single shared vision bodes poorly for formulating an imperative solution to this global time bomb.

An inter-organizational consortium can be formed to address such a problem, whether pertaining to elimination of pollution or development of technology, infrastructure, or resources. Shared risk and responsibility can be established through negotiation and cross-contracting to define the vision, pool capital, share technology, and create market demand of sufficient magnitude to bring such megaprojects to fruition.

Since all prospective players are currently citizens of Planet Earth, the scope of their consortium collaboration can be international as well as national. The scope is determined by the scale of explanatory causes to be uncovered or effects to be achieved through project development. Consortia can be assembled to achieve five possible purposes:

- *Planet Earth protection consortium:* A global R&D fund could be established, supported by taxes assessed on users of pollution-causing products or processes. The funds could be used to identify causes of pollution (thereby further increasing the funding base) or to seed technology innovation that would provide the same effect while preserving the environment (i.e., government-sponsored technological leaps).

- *Technology development consortium:* A mix of designers, manufacturers, and prospective users of a technology should be assembled early on to get the design criteria correct. Seed money could be a mixture of government and private capital. The intent of this consortium would be to involve the companies which would be most likely to develop the spinoff products early, so that their design requirements and insights are fully considered and taken into account. A spinoff surcharge or tax could be assessed as a means of funding the seeding of subsequent generations of research and development.

- *Space exploration consortium:* Exploration is extremely costly and high risk. In the oil business, those who explore and find oil then achieve lucrative payback from either extracting and selling the oil themselves or selling rights to the field. Exploratory missions to neighboring planets could involve a consortium of resource development companies who would be interested in undertaking some of the enormously high risks in exchange for enormously high potential paybacks.

- *Infrastructure development consortium:* It is important that the water, food, power, waste, oxygen, and gravitational systems be compatible in space—to allow for maximum interchange and cooperation among players from diverse nations who might be colonizing space. Agreement on standards is critical to interchangeability of goods and services among participants from different nations. Once standards are set, a vast array of players can begin to develop and market their products and services.

- *Resource development consortium:* Consortia of resource extraction, processing, and manufacturing companies; contractors; builders; equipment suppliers; insurers; and so forth would need to be marshaled to achieve the scale and scope of people and resources required to implement the establishment of a resource-based colony in space. Agreements to fund the costs of installation with loans to be paid back by users or residents of the facility would off-load the burden from the national space agencies to the global business community.

Life Cycle of NASA's Funding Responsibility

The financing required to realize the full array of missions currently on NASA's plate is truly monumental. The exploration projects alone are expected to require more than $60 billion, with more than $100 billion required to operate the various exploratory instruments in space (see table 14) (Broad 1990d).

If NASA's leadership role is to be the exclusive herald of the vision, if its financing role is limited to research and development, and if its charter is clearly defined as syndicating involvement in space exploration and development activities with the private sector, a more realizable long-term agenda emerges (see fig. 14):

- *Phase I (1990-2000): Seed multi-pronged mission initiatives.* This phase requires the greatest amount of independent funding from NASA, but it plants the seeds for user fees and spinoff fees to begin to return in phase II. During the next 10 years Planet Earth monitoring will be initiated; our basic exploration projects will be under way, including the Hubble Space Telescope; more sampling missions will be targeted for the Moon and Mars; heavy funding of the national aerospace plane and controlled ecological life support systems will be provided; and syndication of ownership to enlarge the sphere of producers in space will be promoted.

- *Phase II (2000-2010): Develop an infrastructure support system and do intensive planning.* While some of the initiatives launched in phase I will continue (e.g., Mars sampling missions, capability-driven research), closure on the techniques to be used to support life in space should be achieved. Closure will enable manufacturing companies to begin to produce and market products needed to support humans in space. If these companies were effectively integrated into the early R&D, NASA should begin to collect royalty fees from spinoffs to finance subsequent seed technologies requiring Government-funded nurturing.

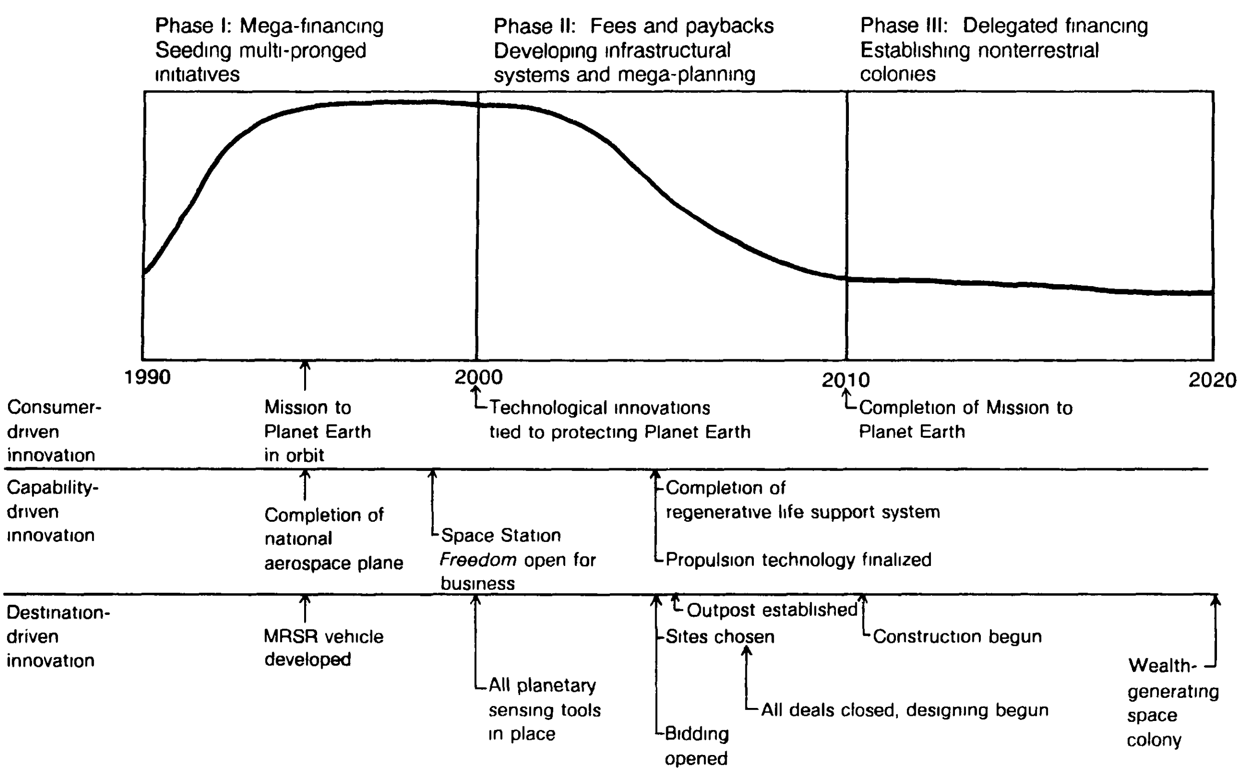
Once the infrastructure technologies and exploration investigations reach closure, mega-planning can begin for colonization of the Moon and

Mars. It will take years to develop detailed designs; negotiate the sharing of risk, responsibility, and rewards; and let contracts. This process may require oversight by NASA, but fees can be charged for bid packages and other services to allay some of the costs.

- *Phase III (2010-2020): Establish colonies on other planets.* This phase should be largely funded by participants, with funds flowing back to the owners and providers of the infrastructure—if it is not an integral part of the project. As colonization begins, products and services—on Earth and in space—should be completely revolutionized, leading to a planetary wealth beyond our wildest imagination: There will be an abundance of resources available from space, new products developed to exploit space, and an abundance of demands that can be met here on Earth as a result of the expanded resource base.

Figure 14

Life Cycle of NASA's Funding Responsibility



We stand at the base of a learning curve that extends to the end of time. The expertise we hold in hand is equivalent to our very first steps, and the targets of our shuffling are most undaring—our closest neighboring planets. Our notions of "high tech" living are being edited daily, as our planetary civilization rushes toward its rendezvous with destiny.

There is new expertise to be honed, new products to be invented, new processes to be engineered. The reality of geotechnology, "which spreads out the close-woven network of its independent enterprises over the totality of the earth" (de Chardin 1972, p. 119), suggests that there is not much point to going it alone—technology is meant to spread like wildfire.

The specific mission objectives sketched out in this paper may not endure; the objectives may change, or from the resulting innovations may come small steps that lead to a higher insight. Advances in our ability to move swiftly and surely up the learning curve are as critical to our future success as our specific achievements. How business systems can be redefined to protect the planet, how technologies can be pushed to their highest performance levels, how new technologies can be created, how sites can be developed in a more humane fashion, how a massive multi-organizational endeavor can be coordinated as if it were a single body, these are the methodologies we are in search of perfecting, equal in importance to the truths we are striving to uncover.

Less than microscopic creatures from the vantage point of the Moon, totally dependent on our 1-pound brains and less-than-1-pound hearts to navigate us toward the unknown and decipher its messages, we human Earthlings have no more powerful resource at hand than our ability to visualize, commit, lead, and actualize—truly incredible abilities that effectively create our future. Our willingness to center ourselves in a common vision—a shared notion of greatness—will abundantly energize us toward fulfillment of even our most elusive goals.

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The Future of Management: The NASA Paradigm

Philip R. Harris

Management Challenges From a New Space Era

The prototypes of 21st century management, particularly for large-scale enterprises, may well be found within the aerospace industry. The space era inaugurated a number of projects of such scope and magnitude that another type of management had to be created to ensure successful achievement. The pushing out of the space frontier may prove to be a powerful catalyst not only for the development of new technologies but also for the emergence of *macromanagement*.

With further extension of human presence into space during the next 25 years, new opportunities will be offered to those responsible for such projects, whether in the public or in the private sector. Satellite expansion, a space station, and possibly a lunar outpost will require new technologies and systems for more complex missions that involve multiple locations and greater numbers and varieties of personnel. Whether in activities of the National Aeronautics and Space Administration, the Department of Defense or military branches, the aerospace industry or new commercial enterprises, there will be a passage from the way space operations have been managed for the first quarter century of development to the way they must be led and administered in the decades ahead.

The challenges will be not just in terms of technology and its management but also human and cultural in dimension (see my paper "The Influence of Culture on Space Developments" in this volume). A recent NASA study, *Living Aloft*, begins to describe the human requirements for extended space flight involving diverse spacefarers (Connors, Harrison, and Akins 1985). In an article on extraterrestrial society (1985), William MacDaniel, professor emeritus, Niagara University, aptly described the multiple challenges in terms of just one undertaking of the next decade—a space station:

> Any way that we look at it . . . NASA will be confronted with management problems that will be totally unique. Space station management is going to be an entirely new ball game, requiring new and imaginative approaches if serious problems are to be resolved and conflict avoided.

MacDaniel, a sociologist and cofounder of the Space Settlement Studies Project (3SP) at his university, then analyzed one people management dimension that results from the sociocultural mix of international scientific and engineering teams and onboard space crews. The multicultural inhabitants of the space station will have to cope with many practical aspects of their cultural differences—differences that alter their perceptions and ways of functioning relative to everything from communication and problem-solving to spatial needs and diet. Whether the orbiting of increased numbers of people for longer periods of time is done by the U.S.A. or the U.S.S.R., Japan or Europe, project leaders will have to include managing cultural differences and promoting synergy among their priorities (Moran and Harris 1982).

In any event, futurists, students of management, and those concerned with technological administration would do well to review the literature of emerging space management for its wider implications. NASA offers a paradigm, or demonstrated model, of future trends in the field of management at large.

The Apollo Heritage in Innovative Management

A transformation is under way from industrial designs of organization and styles of management to a new work culture (Harris 1983 and 1985a). In an AT&T report on emerging issues, the term *metaindustrial* was used to designate the new management and the approach to human systems that is evolving (Coleman 1980). One catalyst for this transition may very well have been the inauguration of the space program by NASA around 1960. NASA, in conjunction with its partners in the aerospace business, innovated in more than space technology. Because of the very complexity of the Apollo lunar mission, NASA also invented new ways of organizing and managing.

> The Apollo project which landed a team of American astronauts on the Moon is generally considered as one of the greatest technological endeavors in the history of mankind. But in order to achieve this, a managerial effort, no less prodigious than the technological one, was required.
>
> (Seamans and Ordway 1977)

It is my contention that much of what is currently being characterized as the "new management" is partially the heritage of that space effort, a harbinger of tomorrow's management. This idea is especially pertinent to the building of large-scale technological projects, whether on this planet or in space. Those engaged in complex endeavors that involve many systems, disciplines, institutions, and even nations will have to apply in even more creative ways the legacy that the Apollo program gave to management (Levine 1982). Investigations should be directed to what constitutes *macromanagement*. McFarland (1985) sees this term as meaning "postindustrial management," while I understand it to refer to "the management of macroprojects" (see fig. 15).

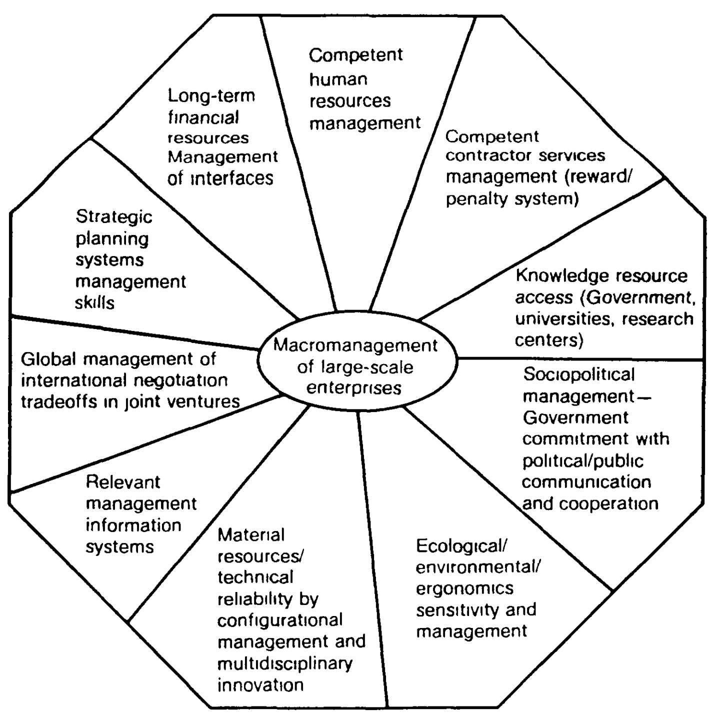

Figure 15

Macromanagement of Large-Scale Enterprises

The management of long-term projects costing $100 million or more will have many aspects. Examples of such "macroprojects" are rebuilding American infrastructure and building a space infrastructure.

In the inaugural issue of *New Management*, the editor listed 10 orientations that lead to organizational excellence today (O'Toole 1983). An organization can excel if it is oriented toward

1. Tomorrow—attuned to the long-term future
2. People—developing human resources
3. Product—committed to the consumer market
4. Technology—employing the most advanced tools
5. Quality—emphasizing excellence, service, and competence
6. External environment—concerned for all stakeholders
7. Free-market competition—imbued with the spirit of risk-taking capitalism
8. Continuing examination and revision of organizational values, compensation, rewards, and incentives
9. Basic management concerns—making and selling products or providing services
10. Innovation and openness to new ideas—nurturing and encouraging those who question organizational assumptions and propose bold changes

Dr. O'Toole was later (1985) to elaborate on this theme in a book entitled *Vanguard Management*.

An examination of the history of the Apollo Program indicates that NASA leaders followed such principles. A possible exception is the third item, which does not quite apply to a public agency, but leaders among the aerospace contractors must have had this concern for the consumer (in this case NASA itself) or the Moon mission would not have been so successful. NASA, over two decades ago, anticipated the emergence of metaindustrial management. The very scope and complexity of putting humans on the lunar surface forced such innovations.

Among the many management innovations to come out of the space program was the matrix organization, with its emphasis on team management. The complexity of the Apollo undertaking necessitated its creation because traditional management approaches proved inadequate. Among the many space contractors, TRW Systems in Redondo Beach, California, was a leader in this process, which was eventually to become a chief feature of the "new" management two decades later. Their vice president at the time, Sheldon Davis, pioneered team building as a means to help technical people work together to reach a common goal (Harris 1985a). Other contractors used the project management and team strategy as a form of ad hoc organization for new starts. General Dynamics, for instance, could quickly assemble experienced team members for its Shuttle-Centaur project from previous work groups that had developed the Atlas-Centaur rocket.

A principal exponent of the matrix as a way of managing complex space projects was Hughes Aircraft. One of its executives, Jack Baugh, did a doctoral dissertation in 1981 on how decision-making is accomplished through a matrix organization. His thesis was that matrix management is essential to an aerospace project when simultaneous decisions are needed in a situation of great uncertainty generated by high information-processing requirements; when financial and human resources are strongly constrained; when the decision-making process must be speeded up; and when the quantity of data, products, and services would otherwise be overwhelming. Obviously, managers outside the space fraternity agreed, adopting the method.

Today a profile of a metaindustrial organization would include these characteristics (Harris 1983 and 1985a):

- Use of state-of-the-art technology, ranging from microcomputers to robotics
- Flexibility in management policies, procedures, and priorities, continuously adapting to the market—a norm of ultrastability (that is, building continuous change into the system)
- Autonomy and decentralization, so that people have more control over their own work space and are responsible for decisions yet work under integrating controls
- Open, circular communication with emphasis on rapid feedback, relevant information exchange at all locations, networking, and the use of multimedia
- Participation and involvement of personnel encouraged, especially through team, project, or matrix management
- Work relations that are informal and interdependent, cooperative and mutually respectful, adaptive and cross-functional

- Organizational norms that support competence, high performance, professionalism, innovation, and risk-taking, even to making allowance for failure occasionally
- A creative work environment that energizes people and enhances the quality of worklife, so that it is more meaningful
- A research and development orientation that continually seeks to identify the best people, processes, products, markets, services, so as to achieve the mission

It is interesting that many of these qualities were identified 15 years ago as essential to the interdisciplinary character of large-scale endeavors (Sayles and Chandler 1971). These were also the characteristics practiced, to a great extent, by NASA management in the Apollo era (Levine 1982). They are considered essential for organizational excellence now and in the future, particularly for large-scale programs such as renewing the American infrastructure or developing a permanent presence in space.

Because those in the management of research and development, especially those coming from engineering and technological fields, may have some misconceptions about the management process, I have included figure 16. This paradigm by R. Alec Mackenzie (1969) illustrates the comprehensiveness of management activity. The conceptual model is a multidimensional approach to the art and science of managing both human and material resources effectively. It highlights, among its central facets, the management of change and differences. This paradigm still seems relevant for managing large-scale undertakings, whether on Earth or in orbit. From my viewpoint as a management psychologist who has served as a NASA consultant, it would appear that the main difficulties facing space management in the future will be found on the right side, in the people dimensions. Unfortunately, this opinion was confirmed by the Presidential Commission on the Space Shuttle Challenger Accident, which concluded that there had been a human systems failure within NASA and its contractors, particularly in regard to information flow and decision-making.

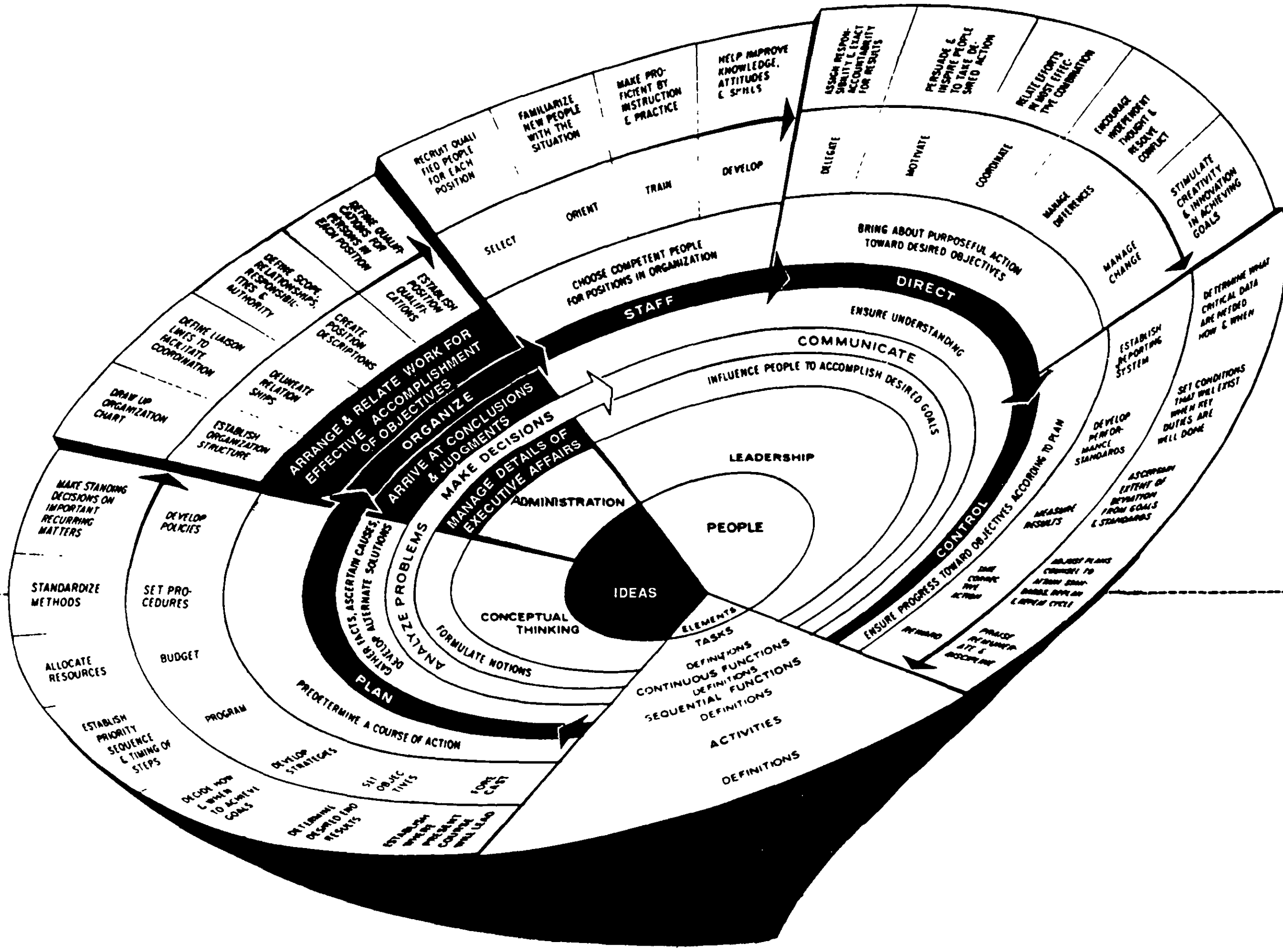

Figure 16

The Management Process

From R. Alec Mackenzie, 1969, "The Management Process in 3-D," Harvard Business Review **47** *(6—Nov.-Dec.): 80-87*

Perhaps the origins of many 21st century management styles may be traced someday to the 20th century management of research and development institutions. Mark and Levine (1984) make a case for such a thesis by pointing to the Federal Government laboratories that promoted the technology development that resulted in macroprograms like the Manhattan Project, the Apollo missions, and the Space Shuttle. They document both technical and managerial innovations produced by bringing together advanced R&D people in relatively small, quasi-independent groups dubbed "skunkworks." Such groups produced some of the most successful modern aircraft. That form of management was eventually popularized by Tom Peters (1982, 1985) as a central theme of the new management leadership.

The Impact of Organizational Culture

The work culture affects organizational planning, decisions, and behavior. MIT professor Edgar Schein (1985) maintains that the work culture is the mechanism for conveying—explicitly, ambiguously, or implicitly—the values, norms, and assumptions of the institution. Organizational culture is embedded and transmitted through

- Formal statements of philosophy or mission, charters, creeds, published materials for recruitment or personnel
- Design of physical spaces, facades, buildings
- Leader role modeling, training, coaching, or assessing
- Explicit reward and status system, promotion criteria
- Organizational fit—recruitment, selection, career development, retirement, or "excommunication"
- Stories, legends, myths, parables about key people and events
- Leader reactions to or coping with organizational crises and critical situations
- Design, structure, and systems of the organization
- Policies, procedures, and processes

In another paper in this volume ("The Influence of Culture on Space Developments"), I analyze the effect of the organizational culture on NASA and the aerospace industry. Figure 17 is a diagram of space organizational culture, which illustrates the many dimensions of a system's expression of identity. Since research indicates that excellent organizations manifest strong functional cultures, NASA obviously did this during its Apollo period. Has it been doing so in the Space Shuttle phase of its development? The 1986 setbacks and subsequent investigations would indicate a negative response. One outcome of current reorganization needs to be a strengthened NASA culture.

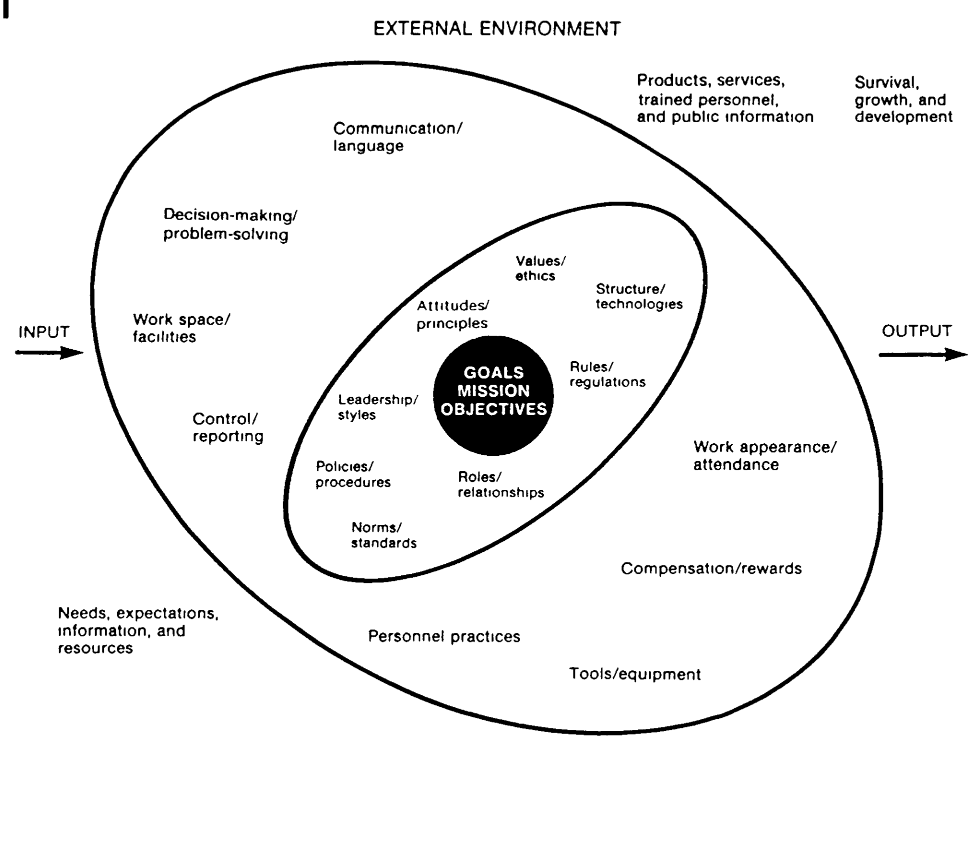

Figure 17

Space Organizational Culture

In 1984, our study team considering space management concluded that a survey and analysis of NASA organizational culture from its headquarters to the field centers would facilitate change and renewal as further space development is planned. If plans for a lunar base are to be effectively implemented, then a transformation in management attitudes, styles, strategies, and operations at NASA may also be necessary. In the post-Apollo era, NASA and its contractors drifted back into an industrial, more bureaucratic style. The work culture, whether of NASA as an organizational system or of its aerospace contract partners, must shift from this industrial or bureaucratic mode back to the mode of enterprises characterized as *metaindustrial*. Only then, it seems to me, will the main actors in the space business be positioned to take advantage of the vast resources on the "high frontier" (O'Neill 1977).

Management consultants see organizations as energy exchange systems. Institutional culture can encourage use of the psychic and physical energies of its people in achieving organizational goals. This is the lesson of the Apollo Moon project. On the other hand, institutional culture can undermine or dissipate the efforts of its people. In order for NASA and its corporate aerospace partners to develop space vigorously in the next 25 years, they must confront the following cultural issues.

(1) The mind-set of the engineer and technologist requires expansion to include generalist thinking. Too often present approaches exclude consideration of human issues, and the contribution of the managerial and behavioral sciences to planning and decision-making are downplayed.

(2) More synergistic relationships in space endeavors should replace obsolete competitive postures by individual companies. The tasks of exploiting space resources are so immense that global space agencies need to collaborate more effectively. Inside NASA, the power games between headquarters and its centers must give way to mutual cooperation. Archaic antitrust regulations must be gotten around to permit aerospace companies to work together to solve common problems, be they matters of quality control on launch pads and space vehicles or greater sharing of

research and development knowledge. The large space corporations can do more for the nation's space program by joint venturing and sharing than by competitive duplication. Furthermore, new ways for synergistic inclusion of university and Government research laboratories should be explored—again as in the Apollo era (Levine 1982). Perhaps the model currently being developed by the European Space Agency is worthy of emulation in North America; it involves cooperation both between nations and between institutions.

(3) As space endeavors reach out to include business participation beyond that of the aerospace companies, attitudes toward and regulations of contractors deserve revision. Perhaps the NASA tradition of partnership with its suppliers is more appropriate than the Department of Defense mentality of seeing its contractors as "users." Space enterprises would benefit from marketplace concerns for satisfying clients and customers (Webb 1985).

(4) Technology development timespans have been lengthened, rather than shortened, because those in the space arena have become more bureaucratic, less entrepreneurial and innovative. From goal-setting to implementation, Apollo's mission was accomplished in less than a decade. Now NASA planners use a 12-to-15-year timeframe from inception to completion of a new technology. Meanwhile, the growing high technology industry (an industry that is a direct spinoff of space technology) has shortened its development timeframe. With due regard to spacefarer safety, perhaps the time has come to reexamine the cultural assumptions by which the practices of redundancy, over-design, over-preparation, over-study, and excessive timidity become embedded habits and traditions. Certainly, such cultural proclivities are less justified in unmanned missions and nontechnical areas, like conference management and reporting. There is reasonable and acceptable risk in the experimental situation of

space flight. What seems more important is effective management of quality control on equipment and parts that go into space transportation systems and habitats.

(5) Organizational renewal implies a continuing process of clarification of roles, relationships, and missions. It requires change from the ways we always did it to the adaptations and inventions necessary to remain a player in the emerging 21st century "space game." Perhaps the habitat modules of space stations and lunar outposts would be better designed by architects and hotel chains than by traditional aerospace vehicle designers. Perhaps the functions of such space facilities should be privatized, so that the NASA centers can take a role more supervisory than operational, thus freeing them for more basic space research and development.

A case relative to cultural issue 2, on synergistic relationships, is the industry-university Consortium for Space and Terrestrial Automation and Robotics (C-STAR). Led by David Criswell of the California Space Institute and sponsored by the NASA-related University Space Research Association, business and academic researchers applying automation and robotics to the space station and other ventures on the high frontier have combined their brain power and established a joint data bank (see, for example, C-STAR Study Group 1988).

The experience with the Shuttle would seem to confirm that NASA moved the project too quickly from research and development into operations. In the transition to 21st century space management, the private sector may dominate the space transportation business and commercial launches, leaving NASA to pursue a technological and scientific research role.

These are but a few of the issues that deserve consideration by management leaders in the space community who would revitalize their organizational cultures and design a management strategy attuned to future demands.

New Roles for Earth- and Space-Based Managers

The five issues just listed are basically cultural and point up the need for planned changes. At our summer study, resource speakers provided numerous suggestions for renewing the American space program and bringing it to new levels of achievement. Several of the more telling comments relate to our topic.

- William E. Wright, Defense Advanced Research Projects Agency, said that the aerospace industry culture is extraordinarily conservative. It suffers from a syndrome: "If it hasn't been done for the last 20 years, forget it." The industry and NASA are not bold enough in their planning and requests for funding. A major program comes into being because someone champions it (puts his reputation on the line and helps bring it into being).

- Peter Vajk, SAI, and Michael Simon, General Dynamics, presented a "stock prospectus" for the establishment of a fictional corporation, "Consolidated Space Enterprises." It envisioned nine companies that could profit by serving customer needs and functions on the space station. Four were providers of such space services as transport, repair, research, and products; three were housekeeping companies that would provide hotel, power, and communication services; two were support companies providing special space services and fuel. The concept of commercial operations on the station, each "feeding" on the other's needs, is not only stimulating to thought but also changes the roles and relationships of public and private participants in space undertakings.

- Peter Vajk, now an independent space consultant, also cited examples of new, more sophisticated management information systems that can alter the role of space project managers. New computer tools, such as relational data base management systems, give managers a better capability to search the literature, while new software like "Hypertext" from Xanadu Corporation (Menlo Park, CA) provides greater access to documentation.

- Ronald Maehl, RCA, pointed out that management issues related to a space station and lunar base represent a departure from traditional NASA management practices. First, there is the matter of managing the development of such projects and precursor missions; then there is the issue of operational management of a space facility when it is functioning. There are precedents in the experience of the National Oceanic and Atmospheric Administration (NOAA) and commercial operators with meteorological and communication satellites. There are new challenges relative to man/machine interactions, operational cost containment, and private participation in such space activities.

These four inputs of experts are but indications of new developments related to the management of tomorrow's space enterprises—developments that warrant more research and call for policy changes by NASA headquarters and its centers. Organizational energy and resources directed to such issues, particularly that of the differences between developmental and operational management, would have greater payoff than the internal struggles of NASA centers to control future programs.

Analysis must be made of the expertise and skills needed by Earth-based managers of projects that are hundreds or thousands of miles away from them. New space project managers have much to learn in this regard from previous project managers of unmanned probes by spacecraft, such as Voyager and Viking, Pioneer and Mariner. The tasks range from limited controls to teleoperations, or the control on Earth by an operator of a machine that is at a remote location such as in space. Management problems experienced include "queuing time" (signal delays between operator command and machine response and between machine response and verification or receipt of data). The management of automation and robotics in space was the subject of another California Space Institute study for NASA (Automation and Robotics Panel 1985).

As more manned space operations occur at more locations, we will need a new infrastructure on this planet to support them. Instead of a single mission control center, there may be regional support centers—some under Government or military auspices and some run by private corporations. For the next 50 years, we are likely to experiment with a variety of Earth-based management plans for space activities, beginning with the space station and a lunar base.

Even more interesting will be management in space of either manned or unmanned ventures. People onsite at a lunar outpost will require more freedom for decision-making and creative problem-solving than the astronauts currently enjoy with mission control in Houston. Decentralized, onsite space management will come into prominence with the building of the space station. Now is the time to begin planning for the practical matters to be faced by station managers, especially when the personnel and organizational components come from various sources beyond NASA itself. In regard to an operational lunar base, research is needed now on such management concerns as communications and leadership and how these functions should be divided between the Earth and the Moon.

Mixed crews (men and women, military and civilian, public and private sector workers, Americans and other nationalities, scientists and other professionals) will invoke more complex management challenges and responses. The people who, in increasing numbers, visit a space station or lunar outpost by 2025 will include more than astronauts or even "astrotechnicians." They will include a broad segment of Earth's society, from politicians to tourists.

In past colonial explorations, trading companies were formed to manage operations in new, remote environs. Perhaps this previous solution could be replicated in a Space Trading Company. If the bold plan for future space developments outlined by the National Commission on Space (Paine 1986) is to be implemented, then more innovative ways for funding and managing space projects will have to be invented. Whether it is financing a fourth orbiter or building a space station, there are historical precedents for national lotteries, selling shares or bonds in space technological venturing, and other forms of public financial participation beyond annual congressional appropriations. The commercialization of space will be a profound force in altering the management of space projects (Webb 1985).

As the crews in tomorrow's space habitations increase in size and heterogeneity, as well as in length of stay away from this planet, planners must expect more stress and strain and must provide space inhabitants with more autonomy, reminds Ben Finney, a University of Hawaii anthropologist, later in this volume. To maximize safe, effective, congenial performance by such pioneers, new programs in behavioral science should be instituted. Studies should be made of team development and group dynamics, new leadership training and responsibilities, and even wellness programs in space communities. Such a program should be part of a planned "space deployment system" I am proposing to facilitate acculturation in a strange, alien, sometimes hostile space environment (Harris 1985b).

For multicultural crews to function well in space, participants must be able to deal with remoteness, they must be self-sufficient and multiskilled, and they must be sensitive to other people and respect the norm of competence. Because space stations in both low and geosynchronous Earth orbit and a lunar or a martian base are such costly, risky, and long-term programs, they will require new management mechanisms that can provide continuity and consistency regardless of personnel changes.

Another management concern to be addressed more vigorously is that of multipurpose missions, such as one involving both civilian and military payloads (Brooks 1983). Economies of scale and piggybacking to contain costs are arguments for combined missions. Technical and management complexity and the issues of secrecy, foreign policy, and international cooperation may prove stronger cases for keeping commercial and defense space activities separate.

Space management would seem an ideal subject on which the Academy of Management and other scholars should focus their research and conferences.

Macromanagement in Space

As has already been indicated, large-scale and complex technical programs require a new type of macromanagement, whether to rebuild this planet's infrastructure or to create a space infrastructure. Figure 15 offers an illustration of the scope of such an undertaking from a management perspective. Long-term projects costing $100 million or more require the application of administrative skills across a range of activities that begins with strategic planning and extends to global or interplanetary management of material and human resources.

Macro-engineering projects have shaped our past and may well shape our future (Davidson 1983). Space programs, like Apollo and the Shuttle, have advanced the field and may be the force behind growth in an allied discipline—macromanagement. Most space programs are macroscopic because they share these characteristics:

(1) They involve difficult, complex engineering and management problems which must be resolved before the program is completed.

(2) They require significant public and private sector resources that must be committed over long timeframes.

(3) They include scientific and technical problems of unusual complexity, size, or circumstances, and the solutions often involve previously unknown technologies or resources.

(4) They have profound impacts on the environment, legal and regulatory situation, economics, and politics of the societies that develop them.

(Davidson, Meador, and Salkeld 1980)

Project management of large-scale enterprises has benefited from such new tools as the program evaluation and review technique (PERT), the critical path method (CPM), and project management space systems (PMSS) modeling. Developments in the supercomputer, software packages, and management information systems have made macroprojects more feasible and manageable. Many of these management innovations owe their origins and refinements to the Department of Defense and NASA.

Macromanagement of large-scale enterprises may very well become a dominant theme in 21st century management practice (McFarland 1985). As NASA seeks to implement plans for a space station in the 1990s and a lunar outpost by 2010, it will not only have to use macromanagement strategies, it may also pioneer in the process. As more corporations participate in space ventures rather than just those in the aerospace industry, NASA will face a new set of interface challenges with these new stakeholders. Already space entrepreneurs expect to launch satellites and a variety of other commercial space ventures that require creating synergy with NASA (Webb 1985). Some of these space enterprises will necessitate the adoption of macromanagement methods.

Research funding should be directed into matters of macromanagement by NASA, global corporations, universities, and others because it demands a new type of management thinking, style, and skills. For example, macroprojects, whether on Earth or in space, stand in need of leadership capable of

- Synergy—facilitating cooperation and collaboration in bringing together diverse elements, so as to produce more than the sum of the parts

- Intercultural skill—overcoming differences between peoples, groups, and nations, particularly through effective cross-cultural communication and negotiation

- Political savvy—gaining agreement and support for project goals from the various political or governmental entities, as well as from the public if their support is essential

- Financial competence—understanding the economic realities of a long-term project and capable of putting together the necessary funding to complete the undertaking, while containing excessive expenditures

- Interface management—taking the lead in bringing together on time the various resources (human, informational, technical, material) required to achieve project goals

- Cosmopolitanism—sensitive to global and interplanetary issues affecting the project, such as legal, ecological, environmental, and human concerns, and able to cope with such issues from an international rather than a national perspective

These are but a sampling of the qualities that are desirable in the new macroproject executive or manager. Perhaps no one person possesses all of them, but a management team may exercise such competencies together. Certainly, a traditionally educated engineer is not likely to possess many of these skills. Research on the education of macro-engineers has been under way at MIT under the conduct of Frank Davidson, and it is beginning at the University of Texas' Large-Scale Programs Institute under the direction of George Kozmetsky. Publications such as *Technology Review*, published by MIT Press, are also addressing these concerns. These efforts should be expanded to include macromanagement as a subject of study. Kozmetsky (1985) calls for transformational management strategies, thus indicating that macromanagement may be one of the central issues of 21st century management.

During our summer study, two resource speakers pointed out existing management models worthy of further analysis by space planners. To create the necessary infrastructures for tomorrow's space programs, consultant Kathleen Murphy (1983) proposed that we could learn from large development projects around the world. (See her paper in this volume.) Such major "greensite" projects have already resolved problems between owners and contractors—developing techniques of conflict resolution and negotiation and making reward and penalty provisions. And they have tested financial arrangements that might prove feasible for space development—including new financing models, joint ventures, consortia, R&D shared between Government and industry, and national bank syndicate investments.

The other input came from consulting engineer Peter Vajk, who observed that global projects concerned with new terrestrial materials may offer insights into the exploration for and exploitation of space resources. Like NASA projects, these projects are high-risk and capital-intensive. They involve very large costs for research and development, startup, and operations. They are beginning to use a macromanagement approach in which a corporate headquarters sets general policy, negotiates major contracts, and keeps accounting and systems records, while subsidiary facilities operate under distributed or semiautonomous management. Projects in new terrestrial materials, being technology- and skill-intensive, involve macro-engineering. They own, lease, or hire their transportation. They operate distribution centers, retail outlets, and sales offices. Their programs are extended in time and space throughout the deployment and operation phases. Their activities are transnational. They use sophisticated computer information networks involving high-rate data transfer. Vajk believes that macroprojects to develop nonterrestrial resources can operate like these Earth-based analogs: "Space is just a different place to do the same kinds of things we do on this planet."

But space is a place for large-scale endeavors of a peaceful and commercial nature. It opens opportunities for human institutions and governments to produce synergy, not war. It requires not only new mind-sets but new management. Over a decade ago, a classic work provided us with a charter for that purpose. In *Managing Large Systems: Organizations for the Future* (1971), Sayles and Chandler reminded us that such enterprises are interdisciplinary in character and integrate an array of scientific, technological, social, political, and other personalities and resources. This charter describes the large-scale programs of NASA, as was well understood by the key administrators of the Apollo Program.

In 1986 the National Commission on Space, appointed by the President, issued a report, *Pioneering the Space Frontier*. It recommends spending $700 billion on the U.S. space program for manned settlements on the Moon within 30 years; a new generation of spacecraft that could voyage to the Moon, Mars, and beyond; and a new space infrastructure for interplanetary factories, spaceports, and communities to accommodate eventually one million space travelers a day. Macroprojects, such as will be undertaken in space by the turn of this century, need more than bold vision; they need a system for managing continuity over long periods, despite fluctuations in personnel, policy, government administrations, and finances. Gaining a national consensus to support new space ventures is a cultural problem. Implementing plans for that purpose implies innovative approaches to space management, such as have been discussed here.

For existing space organizations, such as NASA and its aerospace partners, reeducation of personnel is in order to prepare for the future demands of space management in general and macromanagement in particular. New executive and management development programs should be designed to deal with these considerations. Technology or R&D managers need to become more general in their outlook, more open to new ideas outside their own fields and industries, more competent in management skills. For this to happen, schools of engineering and business will have to design joint curricula, while corporate specialists in human resources and development will have to cooperate with R&D professionals to create more appropriate in-house training.

Space management in the future will necessitate crossing traditional academic disciplines and industrial fields, as this quotation of Frank Davidson (1983) so succinctly implies:

> Space development is a critical case-in-point, because it will test the ability of our diverse, rather relaxed society to set long-range goals, to hue [*sic*] the line despite disappointments and setbacks, and to devise institutional arrangements that will assure continuity. . . . Low-cost approaches are indispensable, because an increasingly educated public will rightly insist on [a] return on investment. . . . Now is the time, therefore, for the aerospace community to reach out to the mining industry, the heavy construction industry, and the ground transportation industry, so that joint ventures on land and sea, as well as "up there" may set a pattern of partnership and a network of personal relationships which will benefit all systems engineering programs that are so necessary for the future health, safety, and prosperity of the Republic.

Conclusions

Under the leadership of NASA, plans are being made for space developments in the next 25 years. At a minimum, the program will include space and lunar stations that will be complicated to construct and manage, require a new generation of technology, and cost billions of dollars. From these bases in space, planners envision mining the Moon, possibly mining an asteroid, and eventually launching manned missions to Mars (maybe a joint mission with the Soviets). Such developments will require an organizational transformation of the National Aeronautics and Space Administration. This may involve structural changes that give the agency more autonomy and flexibility, especially long-term financing. Certainly, it should include planned organization renewal so that NASA builds on the technological and management innovations of its Apollo heritage. If the national decision is to go to Mars jointly with the Soviets, then the challenge will be the integration of the two countries' space management systems.

To become and remain fully metaindustrial, NASA and its aerospace partners will have to create a new work culture. For that purpose, I have proposed a survey and assessment of their current organizational culture, so as to ascertain what changes are necessary for future space management. For NASA, the management changes involve new relationships with the military and the private sector, as well as with international space consortia and possibly some new entities, such as a global space agency.

Obviously, the next 25 years in space will also alter the way we manage enterprises in space. Initially, we need more research on issues of leadership for Earth-based projects in space and space-based programs with managers there. The days of the traditional "mission control" may be waning. Second, we need to realize that large-scale technical enterprises, such as are undertaken in space, require a new form of management. Therefore, NASA and other responsible agencies are urged to study excellence in space macromanagement, including the necessary multidisciplinary skills. Two recommended targets are the application of general living systems theory (Miller 1978; see also his paper in this volume) and macromanagement concepts (McFarland 1985) for development and operation of a space station in the 1990s. Such management models may supply the positive orientation now needed in planning America's aerospace future.

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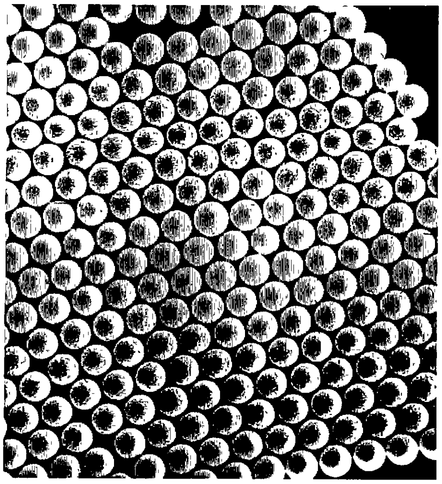
Space Law and Space Resources

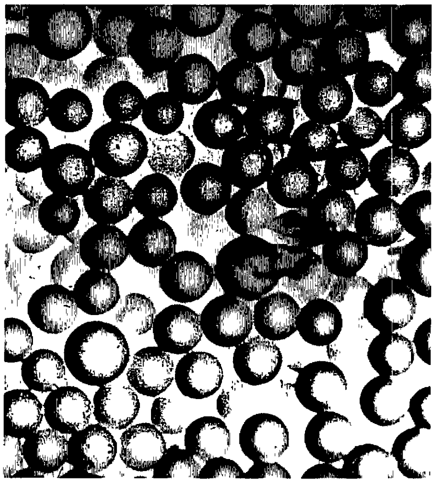
Nathan C. Goldman

Law is not immutable; it responds to the needs of society. Since World War II, humanity has moved increasingly into outer space, encountering new conditions and new needs along the way. The law of outer space has addressed the new political, economic, and technical needs that accompany this transit of human society into space. Space law has been expressed in broad, vague principles that have permitted the maximum flexibility necessary for exploratory space activities. But, as exploration gives way to settlement, this predominantly international law lacks the specificity and legal certainty necessary for mature commercial activity.

Space industrialization is confronting space law with problems that are changing old and shaping new legal principles. Manufacturing in space and exploiting nonterrestrial resources pose economic and political issues that the nations must address. Space exploration has been conducted in the names of peace and humanity; yet, the increasing awareness of the value of space exploration and space applications dictates a new consideration of the merits of international competition and international cooperation in space.



(a)



(b)

Space Manufacturing

a. Latex beads produced in the microgravity of space

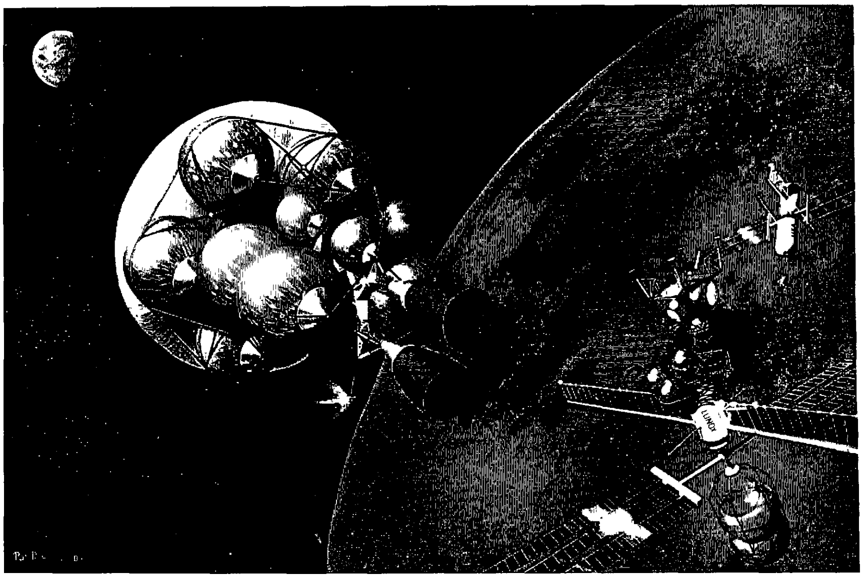
b. Latex beads produced in Earth's gravity

In the microgravity of low Earth orbit, perfectly uniform spheres of latex can be manufactured. Compare these produced on the Space Shuttle (a) with those produced on Earth (b). Note that the products influenced by gravity are of different sizes and sometimes deformed.

Shipping Lunar Oxygen

In this concept, based on a model by Hubert Davis of Eagle Engineering, a lunar lighter is delivering oxygen produced on the Moon to the LUNOX propellant storage depot in lunar orbit. A lunar freighter, equipped with an aerobraking heat shield, is leaving the storage depot carrying oxygen to low Earth orbit for use as propellant on outward bound journeys. On the other end of the storage depot are two larger tanks of hydrogen for use in the manufacture and shipment of lunar oxygen. In orbit with the LUNOX platform is a small space station providing support to lunar astronauts.

Artist: Pat Rawlings

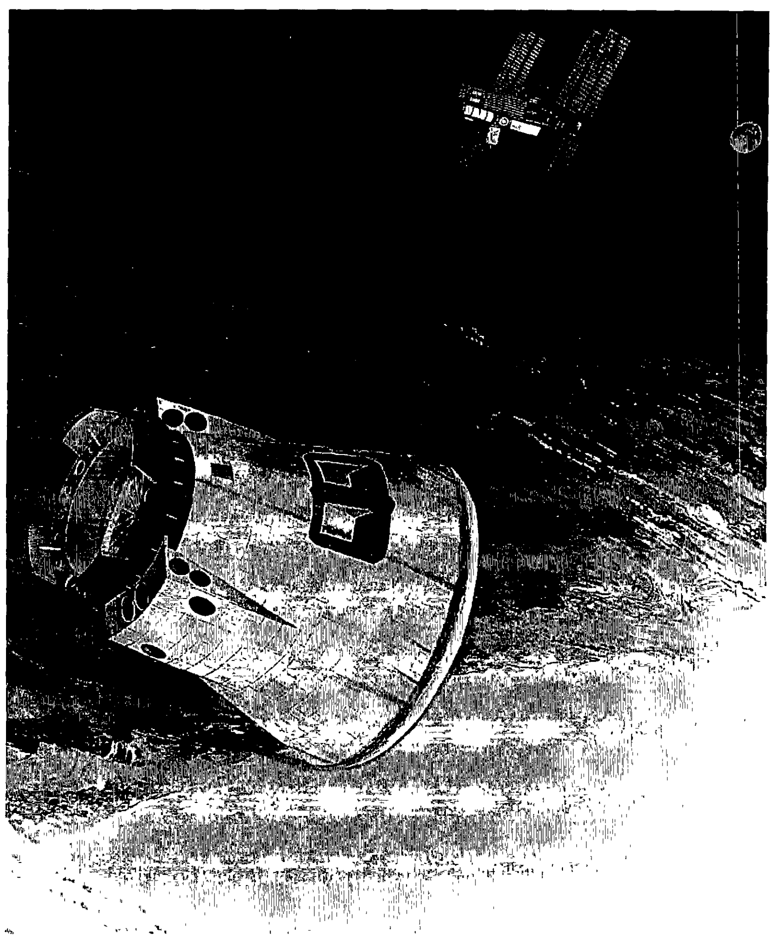


It is given that nations must pursue their national interests. The policymakers in the United States have not always considered well the national interest in space. This lack of policy sophistication resulted in part from arrogance over the American lead in space and in part from ignorance of the importance of space in the future balance of power. Today, with our dwindling lead and with the growing importance of space, the United States must negotiate its international space agreements with the same concern for national priorities that it has in any other international arena. Of course, in any given situation, either cooperation or competition may better serve the national interest.

The Treaties

The U.N. Committee on the Peaceful Uses of Outer Space (UNCOPUOS) is responsible for the major portion of international space law. It has negotiated five treaties. The first four, from 1967 to 1976, have been ratified by the United States, the Soviet Union, and many other nations, active and inactive in space. The fifth treaty, the Moon Treaty, was ratified by the U.N. in 1979 but has been ratified by only seven nations, none of whom has an active space program.

The first treaty, called the Outer Space Treaty or Principles Treaty, has been ratified or acceded to by almost 100 nations. Its broad principles provide the foundation and the philosophy for activities in outer space—that is, a commitment to explore space in peace and for the benefit of all humanity. The second, 1968 treaty—the Agreement on the Rescue of Astronauts, the Return of Astronauts, and the Return of Objects Launched Into Outer Space—expands on the 1967 principle that astronauts are the "envoys" of humanity who should be honored and assisted in every respect (U.S. Senate 1978).



Space Station Emergency Rescue Vehicle

This design is one of several being considered to provide a safe and reliable emergency return from the space station. The Assured Crew Return Vehicle (ACRV) would be based at the space station and use de-orbit engines to return to Earth.

Rescue capability would be offered to astronauts of any nation, as in September of 1988 the United States offered tracking and recovery help to the Soviets when their cosmonauts, Russian pilot Lyakhov and Afghani copilot Mohmand, had difficulty returning from the Mir space station in a Soyuz spacecraft.

Artist: David Russell

Ratified in 1973, the Convention on International Liability for Damage Caused by Space Objects spells out many of the liabilities and duties of spacefarers and describes a procedure to enforce these obligations. The final major treaty, the 1976 Convention on the Registration of Objects Launched Into Outer Space, expands on the 1967 principle that nations retain jurisdiction over and responsibility for their facilities and objects in space. It mandates that a nation register its launch with a U.N. Registry, and thereby legitimate that nation's jurisdiction over the vessel or facility.

Skylab Is Falling!

Lou Pare, flight controller, marks an area in the Atlantic Ocean, part of the final "footprint" of Skylab, as Gene Kranz, deputy director of flight operations at the Johnson Space Center, looks on. Skylab, America's first space station, was launched in 1973 and served as home for three crews, during 1-month, 2-month, and 3-month stays in 1973 and 1974. The spacecraft (which was not designed to be restocked) was turned off, its orbit decayed, and it broke up as it reentered the atmosphere July 11, 1979. Most of its pieces burned up in the atmosphere. Of the pieces that survived the heat of reentry, most fell into the ocean. Only a few fell on land (some were recovered in Australia); none caused any damage.

The 1979 Moon Treaty builds on another 1967 principle, space for the benefit of mankind, to dictate an international regime that will be established at a future date to regulate space resources "in place," declared now the "common heritage of mankind." Neither the United States nor the Soviet Union is likely to sign this treaty. Nor is the treaty likely to gain wide acceptance, authority, or standing as law. Nevertheless, the treaty does represent the most complete international effort to date to deal with the legal and public questions of colonizing and exploiting space.

This thumbnail sketch of space law has been neither comprehensive nor detailed, but it provides a background suggesting serious legal-political problems that will confront the first efforts to mine and use the resources of the Moon and other celestial bodies (Goldman 1988).

Treaty Issues

The utilization of space resources will raise many issues that diplomats and international lawyers need to consider. This section identifies only four of these issues: (1) international competition and cooperation, (2) property rights and nonterrestrial mining, (3) legal liability and responsibility, and (4) environmental impact.

International Cooperation

International cooperation is a theme that pervades the legal regime of space. According to the 1967 Outer Space Treaty, space is to be used for "the benefit of mankind" (Article I). Nations cannot annex or appropriate outer space or the celestial bodies (Article II). The United States has always balanced these more altruistic principles against a second theme: nations are permitted by the treaty to "use" and exploit space. As participant in the negotiations and ever since, the United States has always argued that nations can mine and claim resources "in place" even under the 1979 Moon Treaty (Christol 1982, pp. 293-296).

Photo (just after the start of the run into the Cherokee Outlet, September 16, 1893): L. D Hodges

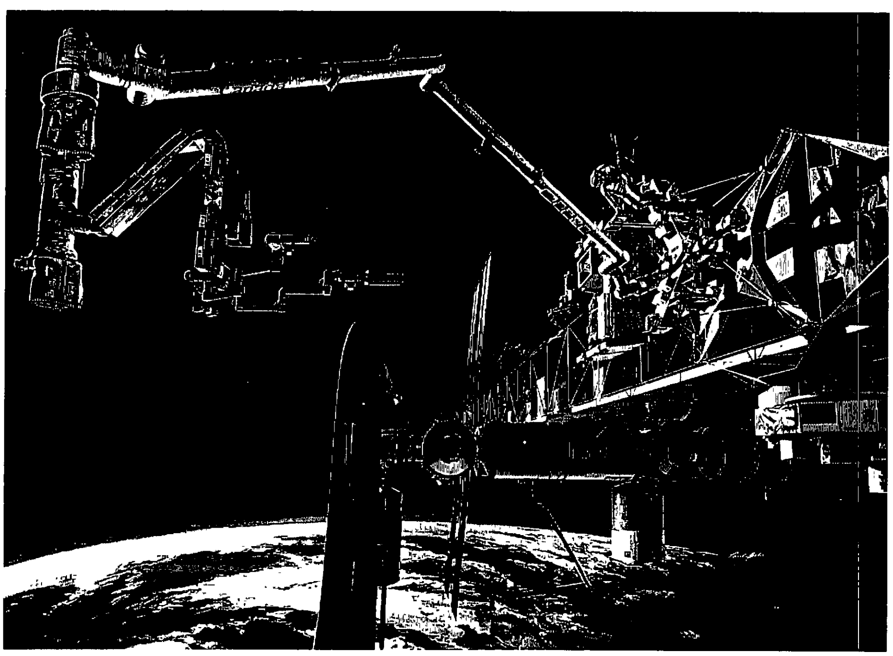
Provided by the courtesy of the Archives & Manuscripts Division of the Oklahoma Historical Society

Oklahoma Land Rush

On April 22, 1889 (some a little sooner), 15 000 settlers from 32 states lined up to make a run into the unassigned lands of the Oklahoma Indian Territory and stake claims to homesteads. Within 5 days a tent city had sprung up on the prairie at Guthrie. International law prohibits the staking of claims to lunar territory, but nations who can get there can use the resources onsite. The United States has always maintained that under the 1967 Outer Space Treaty, which it signed along with almost 100 other nations, and even under the 1979 Moon Treaty, which it has not signed (nor has the Soviet Union), lunar settlers would be able to mine and claim the resources at a lunar base.

Provided by the courtesy of the Western History Collections, University of Oklahoma.

Of course, separate from the legal issue, the United States will need to make a political decision whether to proceed alone or in consortium with other nations. Such cooperation may offset opposition to its activities from many governments, especially in the Third World. Cooperation spreads the risks and the cost of the program; all partners gain from the expertise of the others. Then, the partners can share the technical and financial riches of so momentous an undertaking.



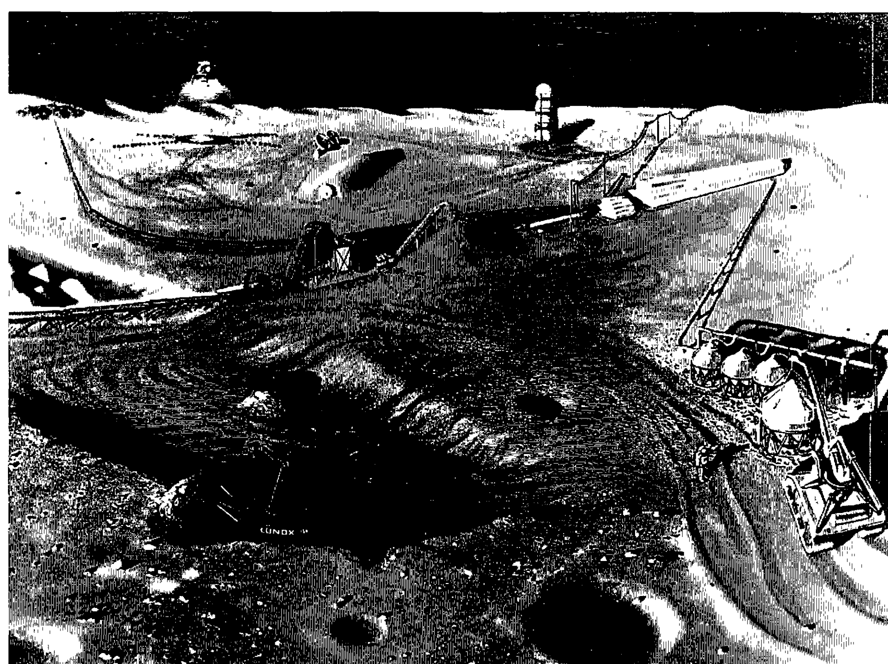
***International Cooperation in Space Station* Freedom**

Cooperating with the United States in the construction and use of Space Station Freedom *will be Canada, Japan, and the nations of Europe. The U.S.A. will supply the habitat module and one laboratory module; the European Space Agency (ESA) will supply a second laboratory module; the Japanese, a third. Canada will supply a mobile servicing center, which will include an improved version of the remote manipulator arm currently in use on the Space Shuttle. It will help assemble the space station and will provide grappling capability thereafter. Such international cooperation spreads both the costs and the benefits of space development. All the partners gain from the expertise of the others.*

Artist: Paul Fjeld

Mining

According to present space law, all mining in space—lunar, asteroidal, or planetary—is treated alike. The operative treaty provisions are (1) that space is reserved for the benefit and is the province of all mankind; (2) that every nation shall have equal access to outer space; (3) that nations cannot appropriate space under any claim of national sovereignty; (4) nevertheless, that nations are free to explore and "use" outer space. The official position of the United States, clearly enunciated in the debates of UNCOPUOS, interprets these provisions to permit any nation or corporation to mine and otherwise use the resources of outer space.



Lunar Mining and Processing

Though international law prohibits the annexation of any part of the Moon, it would allow the use of raw materials mined at a lunar base. In this concept, based on a model by Hubert Davis of Eagle Engineering, bulk soil from a strip mine is delivered by front-end loaders to an automated processing facility. The oxygen won from the process is liquefied and piped to the storage tanks on the right. One filled tank is being loaded now, perhaps to be used at the lunar base, perhaps to be shipped to orbit. The slag is carried by conveyor belt to a dump in the background to the left. Near it, a lunar lighter can be seen landing. The tanks stacked to the right of the buried habitat module contain hydrogen for use in the process and as propellant. Power lines stretch over the ridge to a power station, possibly a nuclear reactor.

Artist: Pat Rawlings

Even under the rather anticapitalist Moon Treaty, the official position of the U.S. negotiators in UNCOPUOS has been that the treaty permitted companies and nations to mine the Moon. For instance, light elements—hydrogen, nitrogen, and carbon—exist in limited quantities in the lunar soil, and frozen water may exist in larger amounts at the lunar poles. Under the longstanding U.S. legal interpretation, the nation finding these resources will be able to mine them. The nation will not own the site, but its labor will attach ownership to the ore (Christol 1982, pp. 39-43). American legal and political planners need to consider the scenario in which spacefarers from another nation go to the Moon and find a singular deposit of volatiles.

American negotiators of the Moon Treaty have argued that the treaty language prohibiting ownership of space resources "in place" means that when the resources have been removed from "in place," personal labor attaches and the mining concern would own the extracted materials. The treaty also envisions that the signatory nations would "undertake" to establish an international regime when utilization of space resources becomes an active possibility. By analogy to the international regime described in the Law of the Sea Treaty (which transfers technology and proceeds from the resource developer to nonparticipants), the regime for space has been vilified by many writers and politicians, and this was a major issue in the defeat of the treaty. The interpretations of the U.S. negotiators evoke alternative regimes, including an international investment organization which nations could join if they desired. Intelsat, the International Telecommunications Satellite Consortium, is such a model.

Although much of the world will object, the legal bottom line on mining nonterrestrial resources is that the United States, the Soviet Union, or any other nation that can get there can mine the Moon and other celestial bodies.

The case of the near-Earth asteroids, however, raises a trickier legal issue. Although a nation cannot appropriate a celestial body, it can use the resources. If space mining basically consumes an entire, small near-Earth asteroid, has the "use," become an "appropriation" of the celestial body? This situation appears to be another example in which the technologies have rendered the treaties obsolete. Perhaps the diplomats need to amend the treaties to redefine these smaller asteroids as a different class of celestial bodies.

Liability and Responsibility

According to the 1967 Treaty, nations are responsible for the space activities of their nationals (Article IV). The Liability Convention in 1973, moreover, established an absolute liability for damages on Earth caused by space activities. Liability based on fault is authorized for damage in space (Article II). Therefore, if the United States decides to take in private industry as a partner in transporting or mining, the U.S. Government would have to monitor these partners closely.

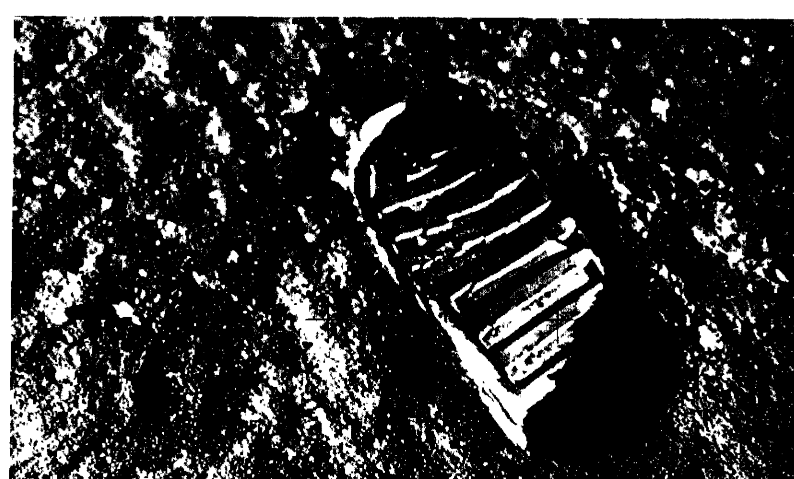
The Liability Convention also provides that nations are jointly and severally liable for damages caused by their cooperative space effort (Articles IV and V). Although the memorandums of understanding or treaties among these national partners will apportion liability and provide a mechanism for settling disputes, the bottom line remains that one nation may be held liable for the entire accident.

Environmental Impact

Two broad concerns for space resources and environmental impact raise treaty issues: (1) back-contamination of Earth and (2) environmental protection of the celestial bodies. The Outer Space Treaty requires consultation about the environmental issues (Article IX). The Moon was seen as sterile, and the rules for back-contamination were not as strict as many scientists wanted. Mars and other celestial bodies may require a different set of regulations. The unratified Moon Treaty suggests that nonterrestrial sites of scientific interest should remain pristine.

Should the Moon Remain Pristine?

"That's one small step for a man, one giant leap for mankind," said Neil Armstrong as he set foot on the surface of the Moon July 20, 1969. His footprints, those of fellow explorer Buzz Aldrin, and the footprints of the 10 other Apollo astronauts to walk on the Moon remain clear and sharp on this windless satellite, despite the passage of 20 years. In fact, the footprints of these astronauts will likely last about 1 million years before they are eroded away by micrometeorite impacts. Development of such nonterrestrial sites will create further disruptions. Where should the line be drawn between protecting the environment and developing the resources?



Conclusions

The return to the Moon, the next logical step beyond the space station, will establish a permanent human presence there. Science and engineering, manufacturing and mining will involve the astronauts in the settlement of the solar system. These pioneers, eventually from many nations, will need a legal, political, and social framework to structure their lives and interactions. International and even domestic space law are only the beginning of this framework. Dispute resolution and simple experience will be needed in order to develop, over time, a new social system for the new regime of space.

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Strategies for Broadening Public Involvement in Space Developments

Philip R. Harris et al.

Rationale

There is widespread public interest in and goodwill toward the space program. For NASA's plans for the next 25 years to be achieved, this public reservoir of support needs to be tapped and channeled. NASA endeavors have to reach out beyond the scientific, technological, and aerospace communities to foster wider participation in space exploration and exploitation. To broaden NASA support and spread out the financing of space activities, we offer these recommendations for consideration.

Economic

For anticipated space missions to be carried out, new sources of income and financial participation should be sought. NASA can no longer operate merely on the basis of annual Federal appropriations. A national commission of financial experts and venture capitalists might be established to analyze the alternatives, recommend to the President and Congress policies and procedures for the public sector, and propose space investments for the private sector. These are a few of the options to be analyzed:

(1) A national or international lottery

(2) A national bond issue

(3) A stock investment plan

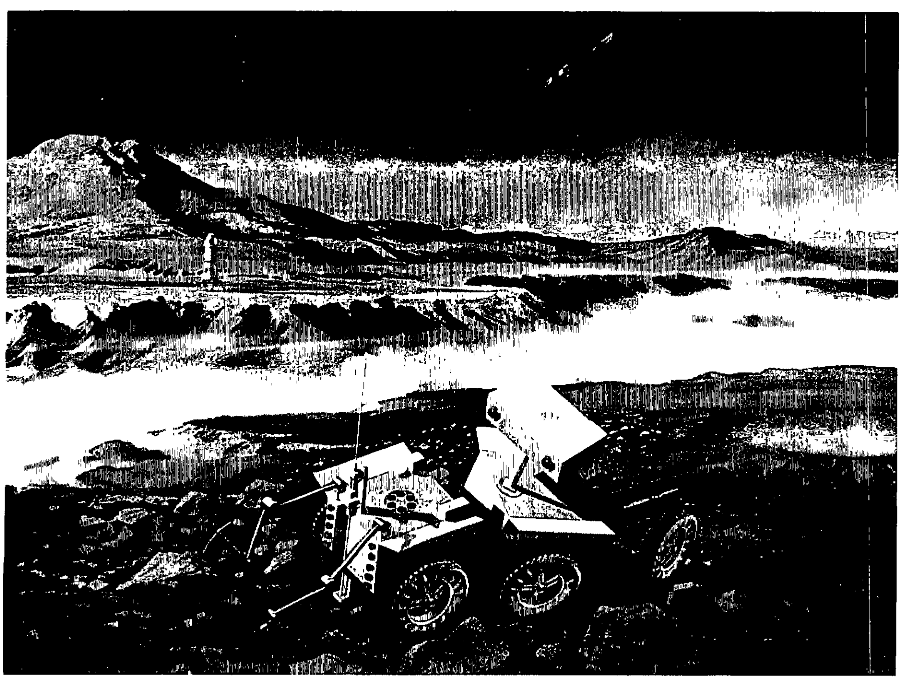
(4) Limited partnership opportunities for space technology

(5) Joint ventures by NASA with other national space agencies or with multinational corporations

Political

To create a national consensus and ethos for space development in the next 25 years, NASA should exercise vigorous leadership on behalf of its intended missions. For this purpose, the following program is recommended to educate politicians, as well as the public, in the scope, necessity, and value of space plans.

NASA needs to decide among the alternative scenarios for space development up to 2010. A plan with specific goals, time targets, and estimated costs, including locations in space and required technology, should be summarized in a case for investment, which is then communicated to all NASA constituencies through a variety of modern media. Using the journalistic who, what, when, where, why, and how as a framework, this case could be put forth in publications, films, videos, and public presentations. To carry this message to the point where public support is transformed into financial contributions, we recommend that NASA focus on the space station, a lunar base, and unmanned explorations, especially of Mars, for the next quarter century. Special briefing workshops might be held for the members of the House and Senate and their staffs, the media, and business leaders. Emphasis should be on the commercial promise of space.



Mars Rover Sample Return

Just as the Apollo lunar samples have been the cornerstones of our knowledge base for planning human habitation and exploitation of the Moon, so martian samples should greatly enhance our ability to plan for exploration of Mars. Analysis of martian rocks and soils would help determine what chemical resources (water-bearing minerals?) are available and what scientific questions human explorers should be prepared to investigate. Plans are currently being made to send robotic sample collectors to several spots on Mars. In this concept, a six-wheeled rover collects and packages samples and delivers them to the launch vehicle in the background which will return them to Earth Each rover/launcher combination could probably provide about 5 kilograms (11 pounds) of samples. Sample returns from various sites on Mars could help select the sites that could be explored with the greatest benefit. In particular, knowledge about martian rocks and soils could help us prepare the tools and techniques to search for evidence of past life on Mars.

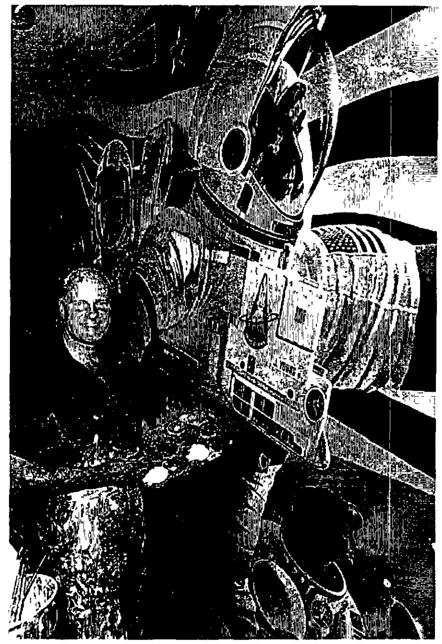
Artist: Ken Hodges

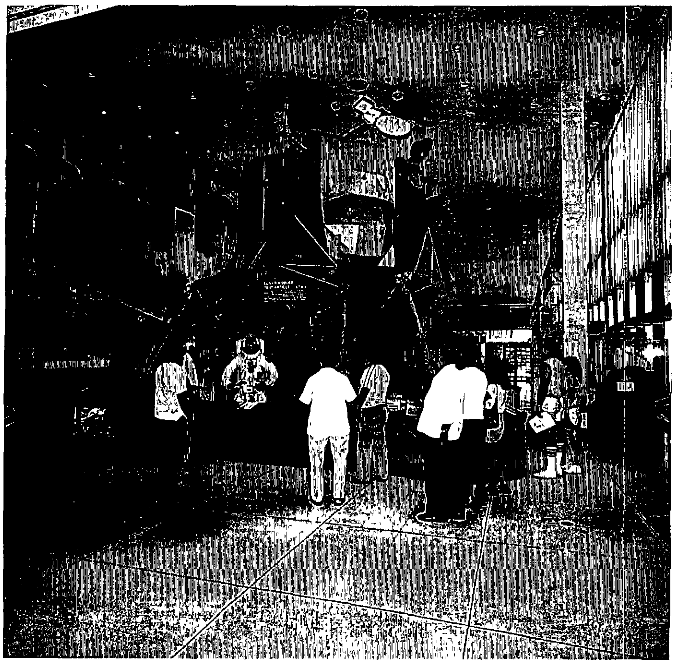
The following means or sources of assistance should be examined:

(1) A White House conference on space enterprise, called by the President at the request of Congress, to consider how to implement the 1986 recommendations of the National Commission on Space. The provisions of the Space Settlements Act (H.R. 4218) might be added to the agenda for discussion. The proceedings could be televised by the Public Broadcasting System and later published in book form for wider dissemination.

(2) A national convocation by NASA of all space organizations, associations, and societies to enlist their support for the NASA plan and to obtain recommendations for private sector involvement in space developments. In addition to gathering their delegates (for example, in conjunction with a Shuttle launch), there might be a teleconference to include their memberships.

(3) An artists' and writers' tour of space opportunities. Artists, dramatists, and film and television producers would be invited to visit key NASA installations and projects to examine the possibilities for collaboration on media projects about space themes, especially those dealing with human migration and communities on the high frontier.





An Artists' and Writers' Tour of Space Opportunities

Robert McCall, NASA-commissioned artist, touches up the middle of a giant mural at the Johnson Space Center's Teague Auditorium. That mural is seen in the background as tourists consider the lunar module test article. Perhaps other artists and writers, including film and video producers, could tour NASA installations to get content for their visualizations of life on the "high frontier." Indeed, Dennis Davidson, art director for the LaJolla summer study and this publication, has made such a tour of the Johnson Space Center with his colleagues in the International Association of Astronomical Artists.

(4) A global space congress on the future of humankind in space, possibly under the auspices of the United Nations or an appropriate international agency. The International Space Year 1992 might be a good opportunity to focus papers and discussions on the kind of space culture we wish to create on the high frontier and whether a global space agency should be formed by the end of this century.

We assume that the proceedings of all the above events would be recorded and published for wider distribution, especially by satellite video.

Institutional

In order to widen institutional support beyond space scientists and engineers, these steps might be considered to enlist professionals and academics in the process of planning space communities:

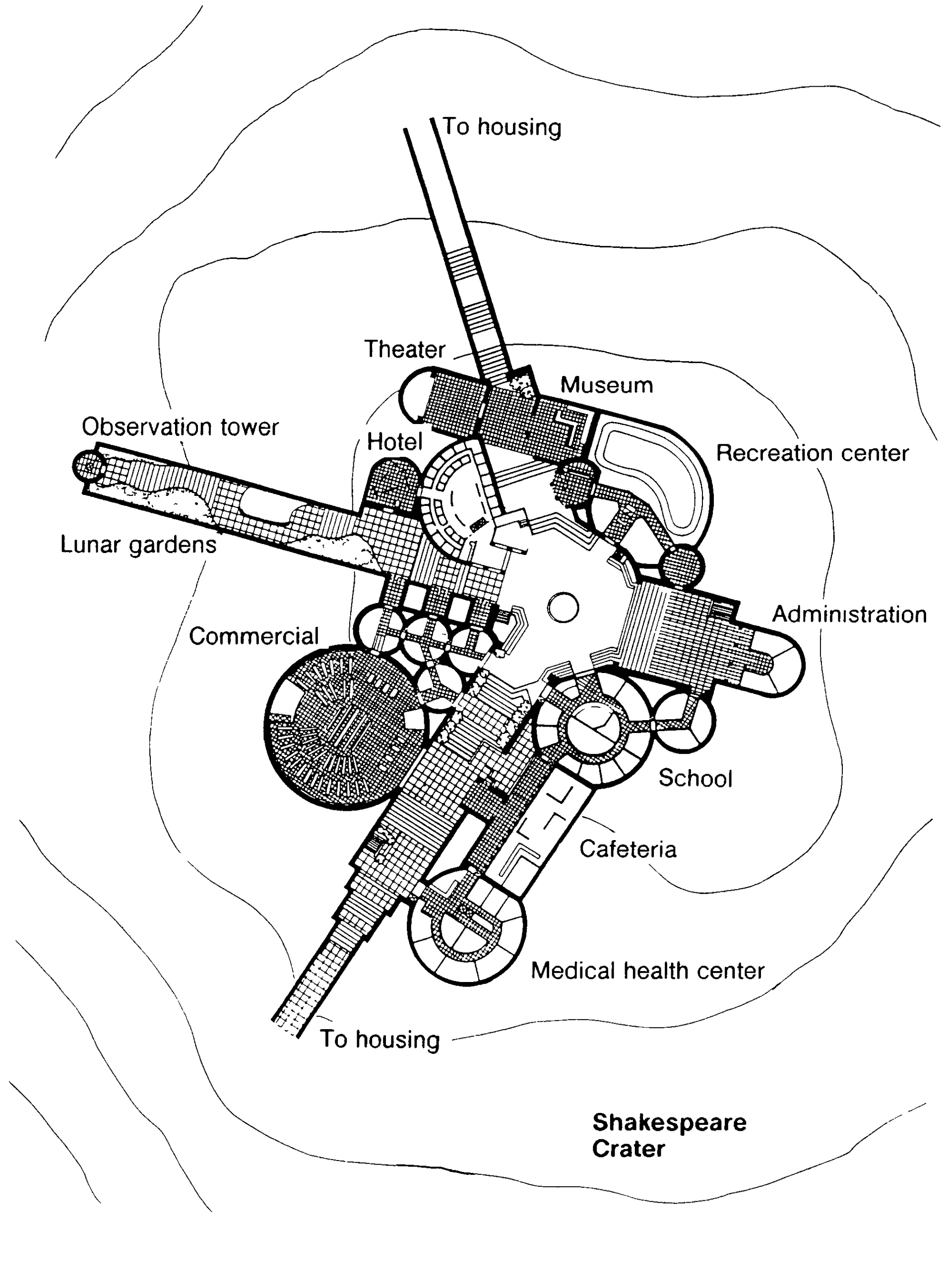
(1) A university presidents' conference might be held to announce new NASA strategies to strengthen the synergy between the agency and the academic community. For example, as a replacement for the summer study approach, NASA might provide grants for specific research it needs to have undertaken on space technology, management, culture, health, and community development. The purpose of this new grant or contract program would be to involve more academic disciplines, such as behavioral and health sciences, in space planning and to foster doctoral level studies and publications that focus on space systems and communities as well as on space technology. Schools of education and human services, for example, might be asked to analyze curriculum changes related to space age developments.

(2) NASA should also reach out to international and national trade associations and professional societies to involve them in space planning. They could be encouraged to conduct conferences, field trips, and even action research on the applications of their fields to space development. For example, medical organizations could examine space health technology and needs.

Similarly, architectural and construction firms, hotel groups, and travel agents could undertake studies of space tourism. Teachers' organizations might focus on space studies for elementary and secondary schools. With imagination, whole new constituencies could be created in this manner, ranging from law to dentistry.

Action Research on Space Health Technology

Skylab astronaut Joseph P Kerwin, M D, serves as a test subject for the Lower Body Negative Pressure Experiment. Astronaut Paul J. Weitz, Skylab 2 pilot and experiment monitor, assists with the blood pressure cuff while Kerwin is in the lower body negative pressure device. The purpose of the experiment, which measures blood pressure, heart rate, the heart's electrical activity, body temperature, leg volume changes, and body weight as well as the pressure produced by the device, is to determine cardiovascular adaptation during a mission in weightlessness, to predict the degree of orthostatic intolerance to be expected upon return to Earth's gravity, and to estimate the ameliorative effect of the device. Such action research is supported by health experts and technology producers on the ground.



Artemis, a Senior Architectural Design Project

The hub of a lunar settlement is laid out in Shakespeare Crater. Vera Rodriguez designed this part of a 21st century community for 3000 inhabitants. She and five other students (Carol Haywood, Ruby Macias, Jorge Maldonado, Larry Ratcliff, and Kerry Steen) in the architecture program at the University of Texas at San Antonio researched, developed, and designed the lunar community as a senior design project under the direction of Dr. Richard Tangum. They were assisted in their research by NASA employees at the Johnson Space Center.

Although designed for the well-being, comfort, and enjoyment of lunar inhabitants, many facilities, such as the observation tower, museum (featuring the history of the lunar settlement), library (in the center of the school), and theater would be of interest to visitors staying in the 100-room hotel, which is expected to be one of the largest profit-making parts of the lunar establishment.

Space Studies

A teacher helps students try on space helmets at an exhibit at the Johnson Space Center. Teacher organizations might be involved in the planning of space communities, thereby enlarging NASA's constituency beyond scientists and engineers. Indeed, Pat Sumi, a teacher in the Gifted and Talented Program of the San Diego Unified School District, involved herself in the 1984 summer study of space resources.

International

To build on those results of the foregoing efforts that have international dimensions, NASA should seek specific joint endeavor agreements with counterpart space agencies and their governments in Japan, Europe, the U.S.S.R., and such Third World countries as China and India. Regional economic associations or multinational corporations (some of which are headquartered in the Third World) might prove suitable for such partnerships. To proceed with this globalization of the space program might require some changes within NASA, such as

(1) Creating in NASA headquarters a structure for this purpose with representation in all NASA centers

(2) Recruiting and training specialists with cross-cultural negotiation and communication skills who can effectively manage such international projects

(3) Identifying ventures in which the complexity of the technology or financing makes an international partner desirable

Managerial

To meet the challenge of a postindustrial society and work culture, NASA needs to plan change in its structure, organizational models, and management policies. We recommend that a task force be established to examine the matters of organizational renewal and development of a metaindustrial work culture. Examples of the issues that might be addressed by this group, with the counsel of external consultants, are

(1) Modernizing and decentralizing operational centers and mission control

(2) Developing a macromanagement approach to large-scale programs, such as building a space station or a lunar base

(3) Fostering a more autonomous, innovative, and entrepreneurial spirit or culture within NASA

Thus can NASA and its management transform itself!

NASA Transformed

In 1975 the official symbol of the National Aeronautics and Space Administration changed from the insignia on the left to the logo on the right. Though many NASA employees feel affection for the old "meatball" and its symbolism (and the official seal of the agency still bears a resemblance to it), even the most conservative can recognize in the new "worm" a positive change of image. The serif type and boundedness of the old circular symbol have changed to the uniform lines of the new, more open symbol and the vertical thrust of its uncrossed A's. This new image represents a streamlined purposefulness in NASA, an organization in the vertical business of launching space enterprises.

Many of the participants in the 1984 summer study at LaJolla advocated more than symbolic renewal for NASA, to energize the organization as it moves out into the solar system.

Space Migrations: Anthropology and the Humanization of Space*

Ben R. Finney

Abstract

Because of its broad evolutionary perspective and its focus on both technology and culture, anthropology offers a unique view of why we are going into space and what leaving Earth will mean for humanity. In addition, anthropology could help in the humanization of space through (1) overcoming sociocultural barriers to working and living in space, (2) designing societies appropriate for permanent space settlement, (3) promoting understanding among differentiated branches of humankind scattered through space, (4) deciphering the cultural systems of any extraterrestrial civilizations contacted.

Space is being humanized. We are learning to live and work in orbit; the era of the actual settlement of the Moon, Mars, and other portions of our solar system seems almost at hand; and talk of eventually migrating to other star systems is growing. My task here is to consider what role the discipline of anthropology might play in understanding and in facilitating this process of humanizing space.[1]

At first glance, anthropology might not seem to have much to contribute to such a highly technical and futuristic enterprise as expanding into space. For example, a recent NASA publication entitled *Social Sciences and Space Exploration* includes chapters on economics, history, international relations and law, philosophy, political science, psychology, sociology, and future studies, but not on anthropology (Cheston, Chafer, and Chafer 1984). That omission is perhaps understandable, because anthropologists have typically focused on the long past of humanity rather than on its future and, when they have studied living peoples, they have usually worked with small tribal or peasant groups rather than with large industrial societies. Yet, despite this seeming fascination with the archaic and the small-scale, the perspective of anthropology applied to space can help us comprehend the human implications of leaving Earth and can facilitate that process.

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[1] A separate paper could be devoted to how remote sensing from space is being used by anthropologists to search for buried or otherwise obscured archaeological sites (see "NASA . . ." 1985), to survey land use patterns of living peoples, and even to track reconstructed voyaging canoes as they are being sailed over the Pacific navigated by Polynesian non-instrument methods (Finney et al. 1986).

An Anthropological Vision

First, and most important, anthropology offers a perspective on humankind that extends back some five million years to the appearance of the first hominids, but it does not end with the evolution of modern human beings and the development of the current high-technology society. Anthropology can help us think about where we are going as well as where we have been. From the perspective of anthropology, we can view our species as an exploring, colonizing animal which has learned to develop the technology to migrate to, and flourish in, environments for which we are not biologically adapted (Finney and Jones 1985). This process began when our distant ancestors developed those first tools for hunting and gathering (see fig. 1), and there is no end in sight. Settling the Moon, Mars, or even more distant bodies represents an extension of our terrestrial behavior, not a departure from it. The technology of space travel, artificial biospheres, and the like may be immensely more complicated than anything heretofore developed on Earth. But, in voyaging into space and attempting to live there, we are doing what comes naturally to us as an expansionary, technological species.

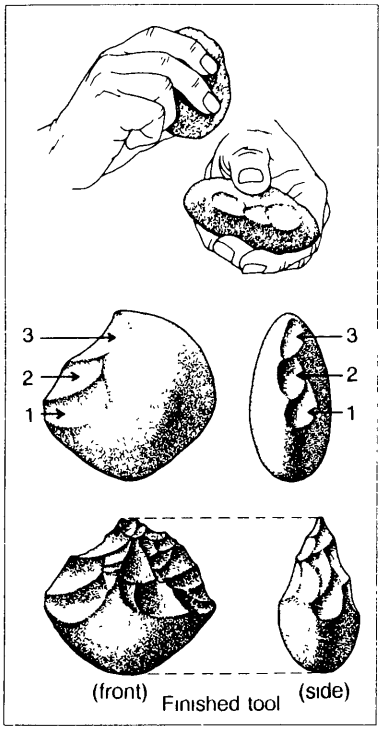


Figure 1

The Beginnings of Technology

Through the development of technology, our distant ancestors were able to spread out of East Africa over the entire globe and to thrive in harsh environments for which we, as basically hairless, tropical animals, are not biologically adapted. The invention of the shaped chopping tool some two million years ago was a major benchmark in this process of technological development. By hitting one rock against another so as to chip off a series of flakes, one can make a crude tool to use in many tasks, such as slicing meat, working hides, and shaping wood and bone into new tools.

Artist: Biruta Akerbergs

Taken from Jolly and Plog 1986, p. 275 Reproduced with permission of McGraw-Hill, Inc.

Yet, settling in space will be a revolutionary act, because leaving Earth to colonize new worlds will change humankind utterly and irreversibly. Anthropologists focus on technological revolutions and their social consequences. The original technological revolution, that of tool-making, made us human. The agricultural revolution led to the development of villages, cities, and civilization. The industrial revolution and more recent developments have fostered the current global economy and society. Now, this same anthropological perspective tells us that the space revolution is inevitably leading humanity into an entirely new and uncharted social realm.

Cultural Analysis

Speculation about revolutionary developments is not, however, immediately relevant to a most pressing question about human adaptation to space: How can groups of people live and work together without psychological impairment or the breakdown of social order in the space stations, lunar bases, and Mars expeditions now being planned? Psychological and social problems in space living constitute, as both Soviet and American space veterans attest (Bluth 1981, Carr 1981), major barriers to be overcome in the humanization of space.

Coping with isolation from Earth, family, and friends and with the cramped confines of a space module or station has been enough of a challenge for carefully selected and highly trained spacefarers of the U.S.S.R. and the U.S.A. As those cosmonauts who have been "pushing the endurance envelope" the farthest attest, staying longer and longer in space provokes severe psychological strain (Bluth 1981; Grigoriev, Kozerenko, and Myasnikov 1985; Oberg 1985, p. 21). Now life in space is becoming even more complicated as "guest cosmonauts" from many nations join Soviet and American crews; as women join men; and as physicians, physicists. engineers, and other specialists routinely work alongside traditional cosmonauts and astronauts of the "right stuff" (see fig. 2). How will all these different kinds of people get along in the space stations of the next decade and the lunar bases and martian outposts which are to follow? What measures can be taken which would reduce stress and make it easier for heterogeneous groups of people to work efficiently and safely and to live together amicably for months or even years in these space habitats?

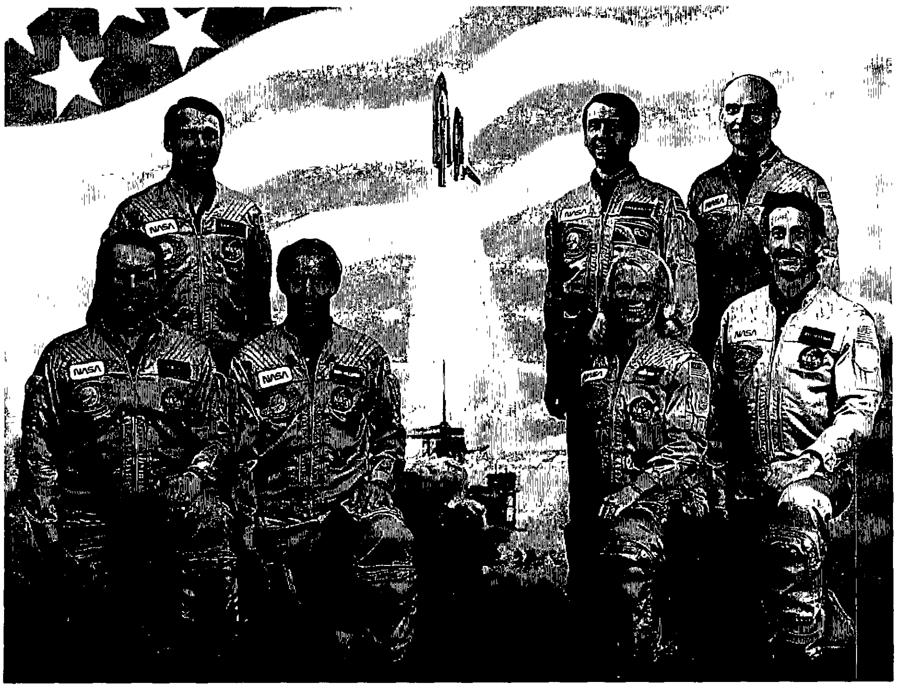


Figure 2

Space Shuttle Mission 51D, Crewed by K. J. "Bo" Bobko, Dave Griggs, Don Williams, Charlie Walker, Rhea Seddon, E. J. "Jake" Garn, and Jeff Hoffman

Space crews are becoming larger and more heterogeneous. Where once space was virtually the sole preserve of military test pilots from just two of Earth's nations, now women, "guest cosmonauts" from a wide range of countries, and physicians, scientists, engineers, and other specialists routinely join traditional astronauts and cosmonauts in space flight.

This trend can be seen in many of the Space Shuttle crews. In this case, Commander Karol J. "Bo" Bobko (Colonel, USAF) and Pilot Don E. Williams (Captain, USN) were joined in their flight, April 12-19, 1985, by Mission Specialists S. David Griggs (another test pilot, with an M.S. in administration), Jeffrey A. Hoffman (Ph.D., astrophysics), and M. Rhea Seddon (M.D.) and Payload Specialists Charles D Walker, representing McDonnell Douglas Corporation, and E. J. "Jake" Garn, representing the U.S. Senate

In the coming era of international space stations, and one day on lunar bases and missions to Mars, a major challenge will be how to structure crew relations so that men and women of many nations, cultures, and occupational specialties can live and work together synergistically in space.

Among social scientists it has been primarily the psychologists (Helmreich 1983), with a few jurists, sociologists, and political scientists joining in, who have tried to address these problems of space living. However, inasmuch as among the diverse lot of people who call themselves anthropologists there are those who are intensely interested in interpersonal relations and small group behavior, it should not be surprising that anthropologists might also be attracted to work in this field. Interestingly, some recent recruits come from maritime anthropology, where they have worked on the dynamics of small-boat fishing crews.

Figure 3

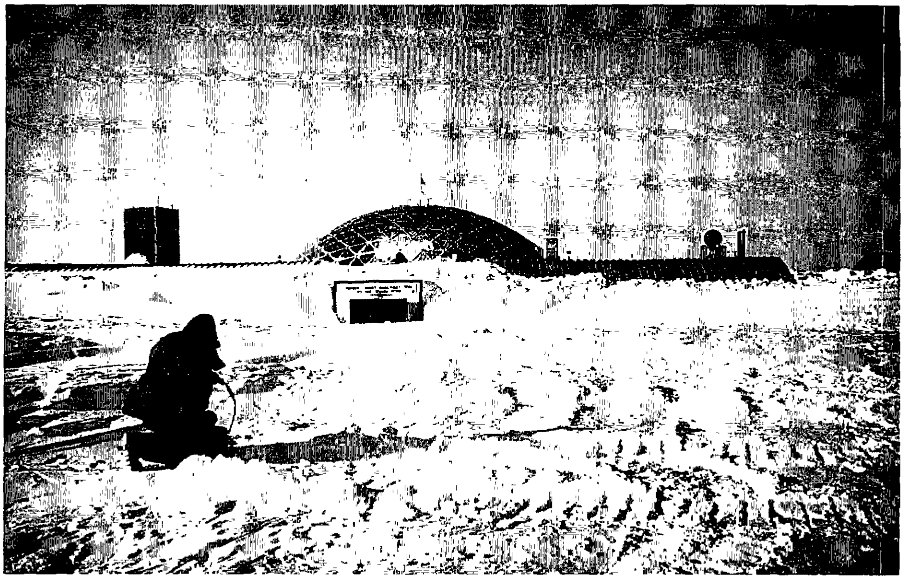
American Station at the South Pole

This station provides one of the closest analogs we have on Earth to a rudimentary base on another planet, in terms of both living conditions and dependence on supplies from outside. The station consists of several buildings—laboratories, service structures, and habitation modules—within a geodesic dome approximately 100 meters in diameter. The South Pole station is continuously inhabited. Crewmembers arrive and depart by air during the summer, but during the long Antarctic winter the dozen or so scientists and support staff live completely isolated from the rest of the world—almost as though they actually were on the Moon.

While the occupants can venture outside with protective clothing ("space suits") during the winter, they are mostly dependent on the shelter provided by the geodesic dome and the buildings within the dome, much as they would be at a Moon or Mars base. Most of the supplies must be brought in by air, but some use is made of local resources. Local ice is used for water, and, of course, local oxygen is used for breathing and as an oxidizer for combustion, including operation of internal combustion engines.

Photo: Michael E. Zolensky

These and other anthropologists interested in space can bring to the field a degree of "hands-on" experience in working with "real" small groups—be they fishing crews, Antarctic scientists (see fig. 3), or hunting and gathering bands (see fig. 4). And they bring a tradition of nonintrusive ethnographic observation and description, which might usefully supplement the more clinical and experimental approaches used by psychologists and other social science researchers. Beyond this, moreover, anthropologists can bring a needed cultural perspective to this pioneering phase of space living.



It is through the concept of "culture" that anthropology has made perhaps its greatest contribution to the formal understanding of human life. In this context, anthropologists mean by *culture* those patterns of beliefs, practices, and institutions shared by a particular ethnic population, a profession, a religion, or another grouping. This concept has diffused beyond the social sciences and, in the United States, has become a common tool for thinking about problems within our multicultural society. It has even crossed the threshold into big business and government agencies such as NASA. One can now read books extolling the "culture" of this or that successful corporation, and I have heard NASA managers explain differences between the Johnson Space Center and other NASA centers as being "cultural" in nature. Here I wish to suggest two specific areas in which this cultural perspective of anthropology could be useful: (1) in addressing the problems of cross-cultural relations among heterogeneous space crews and societies and (2) in the application of cultural resources to develop models for space living.

Figure 4

Agta Men Burning Hair and Dirt From the Skin of a Wild Pig

Here, watched by helpers and children in front of a residential lean-to at Disabungan, Icabela, the Philippines, an Agta man performs the first step in the butchering of a wild pig He burns the hair and outer skin, which he will then scrape off After this, the hunter will cut the pig into shares to be distributed among the band members, and sometimes offered for sale to loggers, farmers, and fishermen who have moved into the area.

Before the invention of agriculture, all of our ancestors lived by gathering wild plant food, hunting wild animals, and fishing. The Agta are representative of the few hunter-gatherer groups still found in the humid tropics of Southeast Asia, Central Africa, and South America. The Agta live in small bands of from 15 to 30 family members along the coast and in the mountains of eastern Luzon Island in the Philippines. They hunt wild pig, deer, and monkey, and they also fish, gather wild plant foods, and plant small gardens of root crops, rice, or maize.

Photo: P. Bion Griffin

Guest Astronauts and Cosmonauts

Foreign Payload Specialists on the Space Shuttle

Ulf Merbold, West Germany, Spacelab 1, November 28-December 8, 1983

Marc Garneau, Canada, Canadian Experiment (CANEX), October 5-13, 1984

Patrick Baudry, France, Echocardiograph Experiment and Postural Experiment, and Sultan Salman Abdelazize Al-Saud, Saudi Arabia, Arabsat-A, June 17-24, 1985

Reinhard Furrer and Ernst Messerschmid, West Germany, and Wubbo Ockels, the Netherlands, Spacelab 4, October 30-November 6, 1985

Rodolfo Neri Vela, Mexico, Morelos Experiments, November 26-December 3, 1985

*Cosmonauts From Outside the Soviet Union**

Vladimir Remek, Czechoslovakia, 1978

Miroslaw Hermaszewski, Poland, 1978

Sigmund Jaehn, East Germany, 1978

Georgiy Ivanov, Bulgaria, 1979

Bertalan Farkas, Hungary, 1980

Pham Tuan, North Vietnam, 1980

Arnaldo Tamayo, Cuba, 1980

Jugderdemidyan Gurragcha, Mongolia, 1981

Dumitru Prunariu, Romania, 1981

Jean-Loup Chrétien, France, 1982 and 1988

Rakesh Sharma, India, 1984

Muhammed Faris, Syria, 1987

Aleksandr Aleksandrov, Bulgaria, 1988

Abdul Ahad Mohmand, Afghanistan, 1988

**List compiled by James E. Oberg, space researcher and author.*

Cross-Cultural Relations

First, consider the issue of cross-cultural personal relations on international space missions. Space is no longer an arena for just two nations. More and more citizens from a growing number of countries are joining their Soviet and American colleagues in space (see list). If this trend continues, it would be easy to imagine a time when crews aboard permanent space stations or the inhabitants of a lunar base would in effect form miniature multicultural societies.

It could be argued that the highly trained and motivated persons who would participate in such future missions would share a common high-technology space culture that would submerge local cultural differences and any problems that might arise from these. That might describe some future situation wherein crewmembers grow up in a common space culture and thereby share common experiences, expectations, and values. However, as long as crewmembers are born and reared in diverse terrestrial cultures, we cannot ignore cultural differences and their potential for generating problems during international missions.

Cultural misunderstandings, stemming from a difference in interpretation of a command or comment or from a clash in behavioral styles, might be deemed trivial and passed over in a terrestrial setting. But they could become greatly magnified on a hazardous mission where people must put up with one another in cramped quarters (see fig. 5) for months, or perhaps even years, at a time. The Soviets, who have had the most experience with international spacefaring, have admitted to cultural difficulties—even though their guests may speak Russian and share a common ideology with their hosts. As Vladimir Remek, a guest cosmonaut from Czechoslovakia, puts it, unique cultural "mental features" can "disrupt the harmony among crew members" (Bluth 1981, p. 34).

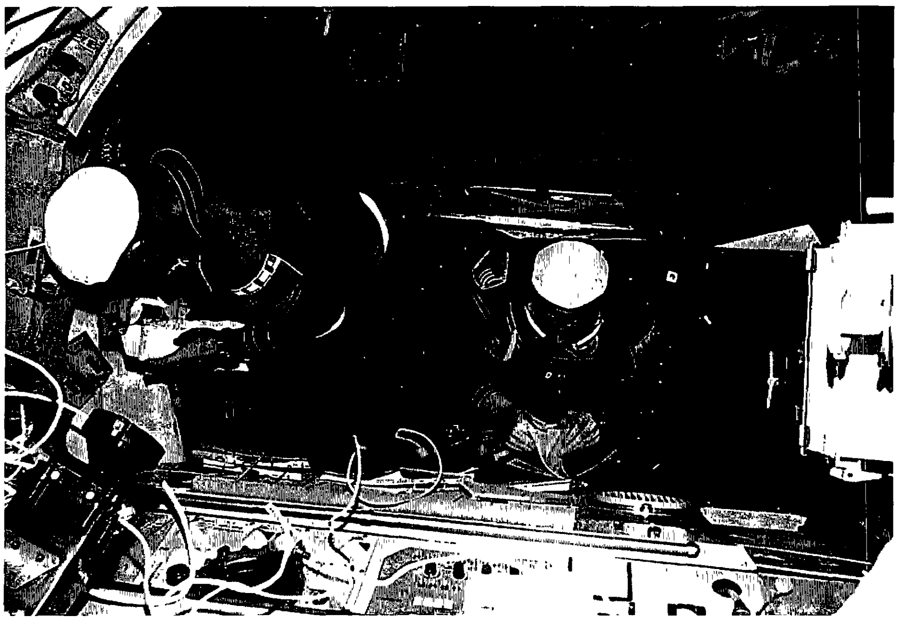


Figure 5

Cramped Quarters

Cosmonauts Valeriy N. Kubasov and Aleksey A. Leonov are seen in the Soyuz orbital module during the joint U.S.A.-U.S.S.R. Apollo-Soyuz Test Project docking in Earth orbit. This photograph was taken by one of the three American astronauts on the mission—Thomas P. Stafford, crew commander; Donald K. Slayton, docking module pilot; or Vance D. Brand, command module pilot. The American and Soviet spacecraft were joined together in space for 47 hours, July 17-19, 1975.

The 47-hour ASTP rendezvous was a success both technologically and culturally, but the cramped quarters of the Soyuz spacecraft [the Apollo spacecraft was equally cramped (see the photo on p. 12)] and the differences in national styles demonstrate the potential for cultural clashes on longer missions with mixed crews.

One prerequisite for group harmony is good interpersonal communication. Basic to that communication is what the anthropological linguist Edward Hall calls the "silent language" of facial expression, gesture, body posture, and interpersonal spacing (Hall 1959). Members of the same culture tend not to perceive how much is communicated nonverbally, because their shared ways of gesturing and moving their bodies may be so culturally ingrained as to be virtually unconscious. They can therefore be greatly taken aback when confronted with members of another culture who gesture or use their bodies differently. Americans, for example, commonly experience a bewildering sense of discomfort when conversing with Middle Easterners, who habitually stand closer to their conversational partner than the American norm. Conversely, Middle Easterners may interpret Americans' greater conversational distance as a sign of coldness or dislike. Take conversational distance and all the other elements of the "silent language," mix well with an international crew in a crowded space habitat (especially one located in a microgravity environment, where facial expressions are made even more difficult to read because of the puffiness of the face from fluid pooling in the head), and you have a recipe for cultural misunderstanding.[2]

Cultural Resources

Cultural factors should not, however, be viewed solely in terms of impediments to successful space living, for they may also constitute valuable human resources to be tapped in adapting to space. In addition to seeking to promote cultural harmony among heterogeneous space crews, we might also seek out, from the multitude of cultural traditions among the Earth's societies, those practices and institutions which could best promote harmonious and productive life in space.

As an example, consider interpersonal problems in a space habitat. J. Henry Glazer, an attorney who has pioneered the study of "astrolaw," warns against exporting to space communities the adversarial approach to dispute resolution based on "medieval systems of courtroom combat" (Glazer 1985, p. 16). In small space habitats, where people

[2]For another perspective on cross-cultural relations in space, see Tanner (1985).

cannot escape from one another but must work out ways of interacting peacefully and productively, adversarial proceedings would irritate an already sensitive social field. And how could the winners and losers of bitter courtroom battles live and work with each other afterwards?

One obvious suggestion is that systems which are designed to detect interpersonal problems early and head them off through mediation should be considered for space living. Glazer, for example, calls for a new kind of legal specialist—not an adversarial advocate, but someone who settles disputes on behalf of the interests of all spacefarers on a mission. He draws his model from the *Tabula de Amalfa*, the maritime code of the once powerful Mediterranean naval power of Amalfi. Their code provided for a "consul" who sailed aboard each merchant vessel with the power to adjudicate differences between master, crew, and others on board (Glazer 1985, pp. 26-27; Twiss 1876, p. 11). In addition to looking to this and perhaps other maritime analogs, it is tempting to suggest that, with an eye to the more distant future of large space settlements, we also examine major contemporary societies in which harmony and cooperation is stressed. The example of Japan, with its low crime rate and relative paucity of lawyers, comes to mind—although its utility as a model for international efforts may be limited in that Japan is such an ethnically homogeneous society (Krauss, Rohlen, and Steinhoff 1984; Vogel 1979).[3]

New Cultures, New Societies

Once we have learned how to live together amicably in space and to work safely and efficiently there, once we have developed ways of avoiding the health problems of ionizing radiation, microgravity, and other hazards of nonterrestrial environments, and once we have learned how to grow food in space and to produce air, water, and other necessities there, then humankind can actually settle space, not just sojourn there. New cultures and new societies will then evolve as people seek to adapt to a variety of space environments.

[3]See Schwartz (1985) for a comprehensive analysis of the utility of various institutional responses to colonizing opportunities made by migrant farmers from a variety of world cultures.

This process of building new cultures and societies will undoubtedly contain many surprises. Yet, all the resultant sociocultural systems must provide the basic prerequisites for human existence if they are to be successful. Here is where the seeming disadvantage of the anthropologist's penchant for studying small communities may actually prove advantageous.

The sine qua non of anthropological experience is a long and intense period of field work in a small community, during which the investigator attempts to obtain a holistic understanding of the group (see fig. 6). For example, I once spent a year living on a small island in the middle of the Pacific with only 200 inhabitants, during which time I learned the language, became well acquainted with every individual and his or her position in the community, and gathered data on everything from fishing and house building to marriage and religion. Because of this holistic experience of studying a small, relatively self-sufficient community and trying to figure out all its parts and how they fit together, I find most discussions of space settlement curiously incomplete. Typically, they go to great lengths to explain how habitats will be built on a planetary surface or in space, how food will be grown in these habitats, and how the community will earn its way by mining or manufacturing some valuable product; then they skip on to few details about domestic architecture, local government, and the like.

Figure 6

a. Building a Canoe in Polynesia

Men of Anuta Island rough out the hull of an outrigger fishing canoe. This Polynesian community, located on a tiny volcanic island off the eastern end of the Solomon Islands, well away from regular shipping routes, has a population of less than 100 people. Its small size and relative isolation makes Anuta an intriguing community for thinking about life in a small settlement on the Moon or elsewhere in our solar system

Photo: Richard Feinberg

b. Thatching a Roof in Polynesia

A communal working group thatches a roof on the island of Nukuria, a Polynesian atoll located in the Bismarck Archipelago near New Guinea. In this atoll community of some 200 inhabitants, people work cooperatively on such chores as roof thatching, much as early American farmers used to help each other out with barn-building "bees." The isolation, small size, and relative self-sufficiency of such island communities allows the anthropologist studying them to gain a holistic perspective on all facets of life from birth to death. This holistic perspective in turn may enable anthropologists to foresee critical human elements in future space settlements that planners who are inexperienced in the functioning of small, relatively self-contained communities may ignore.

Photo. Barbara Moir

Among the crucial elements of human life omitted, or glossed over, in these futuristic projections is the most basic one for the survival of any society: reproduction. How mating, the control of birth, and then the rearing of children are to be arranged is seldom even mentioned in discussions of space settlement.[4] Yet, if our ventures in space were limited to communities of nonreproducing adults whose number would have to be constantly replenished with recruits from Earth, we could hardly expand very far into space.

Of course, it could be argued that no great attention will be required in this area—that people will carry into space whatever reproductive practices are current in their earthside societies. But, would that mean a high percentage of single-parent households and low birth rates? A distinguished demographer, whom Eric Jones and I invited to a conference on space settlement, explained his lack of professional interest in the subject by saying that he really did not think there would be much population expansion into space. He argued that the nations most likely to establish space settlements are those which have passed through the demographic transition from high to low population growth and that, furthermore, the highly educated, technology-oriented people who would be the ones to colonize space are those inclined to have the fewest children, perhaps not even enough for replacement of the population.

A population's demographic past is not necessarily a reliable predictor of its future, however, as we should have learned after the surprise of the post-World War II baby boom in the United States (Wachter 1985, pp. 122-123). It seems obvious that, when people perceive that it is to their advantage to have many children, they will do so. For example, Birdsell (1985) has documented how, in three separate cases of the colonization of virgin islands by small groups, the population doubled within a single generation. Figure 7 (Birdsell 1957) graphs the population growth on Pitcairn Island from 1790 to 1856. Unless radiation hazards, low gravity, or some other aspect of the nonterrestrial environment constitutes an insuperable obstacle to our breeding in space, there is every reason for optimism about the possibility of population expansion in space.

[4]But times may be changing. NASA psychologist Yvonne Clearwater (1985, p. 43) has recently raised the issue of sexual intimacy in space, and law professor Jan Costello (1984) has just published an inquiry into the issues of family law in space.

Nonetheless, the export into space of some current features of mature industrial societies, such as the high cost of educating children, the desire of both parents to have full-time professional careers, and the lack of institutions to aid in child rearing, would certainly act to slow expansion. Space settlers interested in expanding their populations should structure community values and services in such a way that people would want to have more than one or two children and would be able to afford to in terms of both time and money. An anthropological perspective could aid space settlers in constructing a socioeconomic environment for promoting population growth; first, by helping them to break out of the assumption that the way things are currently done in mature industrial societies represents the apex of human development; and, second, by informing them of the wide range of reproductive practices employed by the multitudes of human societies, past and present.

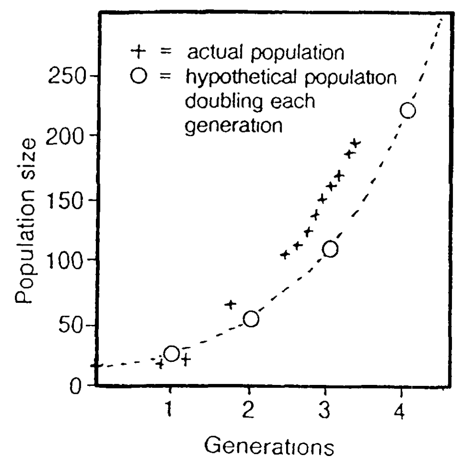


Figure 7

Population Growth on Pitcairn Island, 1790-1856

If physical conditions can be made favorable for human existence on other planets or in orbiting space habitats, the experience of small groups of people colonizing uninhabited islands suggests that our spacefaring descendants may expand rapidly—until checked by resource limitations. In 1790 six English mutineers from the H.M.S. Bounty, *eight or nine Tahitian women, and several Tahitian men settled on the tiny, uninhabited island of Pitcairn. Despite genocidal and fratricidal quarrels among the Tahitian men and the mutineers, the population more than doubled each generation, reaching almost 200 in 1856, when lack of food and water forced evacuation of the island.*

Adapted from Birdsell 1957.

Some of the practices from our remote past might even be relevant to our future in space. Suppose, for example, that the harshness of the airless, radiation-intensive environments of space, combined with the economics of constructing safe human habitats, dictates that the first space settlements would have to be small, containing well under a hundred people (Oberg 1985, p. 183). Pioneering space colonies might therefore be in the size range of the hunting and gathering bands in which most of our ancestors lived before the discovery of agriculture and the consequent rise of urbanization. If so, space settlers might face some of the same problems relating to reproduction as did their distant predecessors: the genetic dangers of inbreeding, random imbalances in the sex ratio of children born into the group, and what might be called the "kibbutz effect," wherein children reared close together are not markedly attracted to one another upon coming of age (Spiro 1965, pp. 347-349).

Our predecessors could avoid these problems with one simple institution: the practice of exogamy, whereby youths had to marry someone from outside their natal group, thus enlarging the effective breeding community to encompass hundreds of persons, not just a few dozen. Of course, it could be argued that sperm and egg banks, in vitro fertilization, and even in vitro gestation and genetic engineering may be so advanced by the era of space colonization that there would be no need for exogamy. Yet, marrying outside of one's group can bring benefits that may not be obtainable by other than social means.

Exogamy can promote social solidarity by binding together otherwise separate and scattered communities into a network of units which, in effect, exchange marriageable youths. Although the Australian aborigines, for example, lived scattered over their desert continent in small bands averaging 25 men, women, and children, they were linked together in tribes of some 500 people (Birdsell 1979). This larger tribal community was more than a breeding unit. At appointed times, the members of all the bands would gather together to arrange marriages, conduct rituals, and enjoy the fellowship of friends and relatives from other bands. Just as this tribal community provided the aborigines with a needed wider social group, so might a space age confederation of intermarrying space colonies help their pioneering inhabitants fight the loneliness of space (Jones and Finney 1983).

Of course, a space age exogamy system would probably not replicate all the features of its archaic predecessors. Take, for example, the custom of female bride exchange, whereby the marriageable young women were sent to other groups, which in turn supplied brides for the young men who remained at home. Space age young women would surely object, on the grounds of gender equality, to any rule that required that they leave home to marry, while their brothers could stay. Conversely, adventuresome young men might not relish the idea that they must remain at home and import their brides. More than likely, if the ethos of space communities is explicitly expansionistic, then both males and females will vie for the opportunity to leave their natal community and, taking a mate from another established community, go off to found a new colony.

Role of Anthropology

Assuming that someday it becomes widely accepted that anthropological insights and findings could help us understand human expansion into space and aid in that process, the question arises: How are those insights and findings to be applied and who applies them?

The suggestion that a corps of anthropologists be recruited to facilitate smooth cross-cultural relations in international space stations, to design appropriate institutions for permanent space communities, and to forecast the biocultural impact of moving into space might bring approval from my space-oriented colleagues and hope to many a new anthropology graduate trying to find a job in today's tight academic market. However, I would not advocate that anthropologists be elevated to the status of elite experts in planning human expansion into space. Anthropology is not an exact science in the sense that it can make accurate and precise predictions. Anthropological gurus of space expansion would hardly be infallible prophets or unerring social engineers. Instead, I foresee a more modest role for anthropologists as students of space expansion and advisors in that process.

The ideal recipients of that advice would not be some earthside planners charged with designing the social structure of space stations, lunar bases, and even more futuristic endeavors. Ultimately, the people who should receive the most appropriate advice on anthropological matters are those who will actually live and work in space. Call it self-design, home rule, or just plain independence, the underlying premise is the same: those who will actually reside in space stations, planetary outposts, and the first true space colonies should have a crucial role in the initial design of their particular community and, above all, in the inevitable modifications to that design which would arise through experience. In this light, the burden of space anthropologists—some of whom must do field work in space if they are to live up to their calling—would be to come up with relevant insights, findings, and recommendations derived from both terrestrial societies and groups in space and to communicate these to the spacefarers and colonists.

Two centuries ago a group of gentlemen farmers, lawyers, and politicians, faced with the task of constructing a viable nation out of a disparate collection of ex-colonies, came up with a remarkable document, the Constitution of the United States, which set out a form of democratic government that has since proved most successful (see fig. 8). This document, and the resultant form of government, was the product of a concerted design process based on a comparative study of forms of government instituted at different times and places through history, a study undertaken not by outside experts but by those who had to live in the resultant nation. I look forward to many such occurrences in space when the space settlers themselves—not earthside planners or even a space-based planning elite—sit down, sift through the accumulated human experience, and come up with principles for the design of new societies adapted to their needs in space. Here is where the anthropological record—from both Earth and space—and the principles derived therefrom could make a major contribution to the humanization of space.

Figure 8

Framing a Constitution for a New Nation, Philadelphia 1787

In framing the Constitution of the United States, a group of gentleman farmers, lawyers, and politicians, representing a tenuous union of ex-colonies, drew upon models of political organization provided by ancient Greece and Rome and other earlier states, as well as the writings of Enlightenment philosophers, to construct a totally new form of government suited to the needs and aspirations of Europeans transplanted to a New World

Some time in the future, when and if spacefaring and spacedwelling technology is sufficiently developed, similar scenes may be reenacted as space settlers—drawing on the accumulated experience of terrestrial polities and inspired by space age philosophers—set out to devise new forms of government adapted to the needs and aspirations of developing nations in space.

Artist: Howard Chandler Christy

If We Are Not Alone

While the solar system appears to be the sole province of humankind, we do not know whether we are alone in the galaxy. Should we have company and should we or our descendants make contact with extraterrestrials, then anthropology might have a new role in space. The experience of anthropologists in trying to bridge cultural gulfs could be applied to the immense task of comprehending an extraterrestrial civilization.

Ten years ago a group of anthropologists and other social scientists published a book entitled *Cultures Beyond Earth* (Maruyama and Harkins 1975) exploring just such an "extraterrestrial anthropology." They assumed actual physical contact, via interstellar travel, between us and the extraterrestrials. To scientists engaged in the Search for Extraterrestrial Intelligence (SETI), however, the prospect of actually making physical contact is extremely remote. They argue that the physical problems and great cost of interstellar travel, as opposed to the relative ease and economy of radio communication, plus the great value that advanced civilizations would place on information, as opposed to physical experience, mean that contact will be made via the electromagnetic spectrum, not in person (Morrison, Billingham, and Wolfe 1977). Although the view that interstellar travel will never occur is arguable, a case can be made that, even if physical contact eventually takes place, speed-of-light radio communication would precede it (see fig. 9). Hence, the question is "What role could anthropology play in cultural analysis at a distance?"

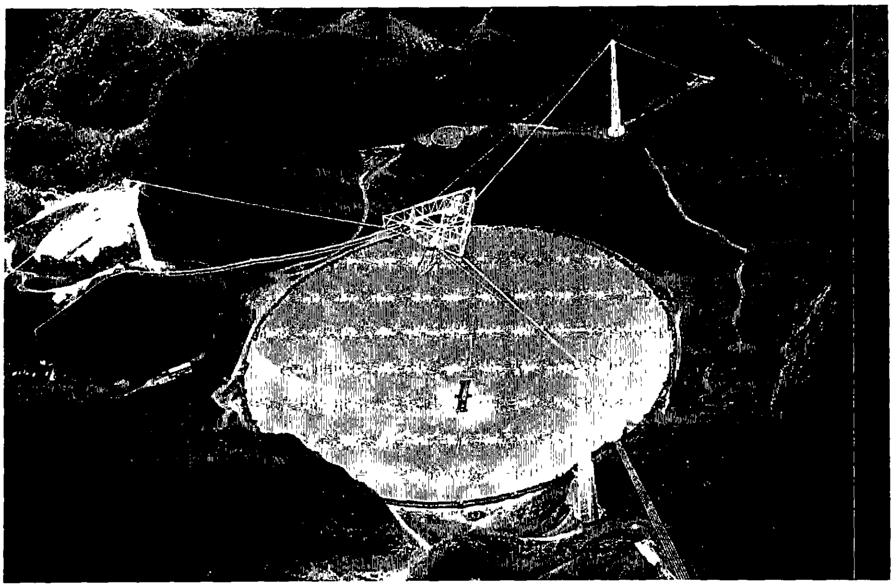


Figure 9

Radio Telescope at Arecibo, Puerto Rico

The world's largest radio telescope (305 meters in diameter), at Arecibo in Puerto Rico, is operated by the National Astronomy and Ionosphere Center at Cornell University under contract to the National Science Foundation. The Arecibo telescope will soon be used by NASA in a systematic search for radio transmissions from other star systems in the galaxy, transmissions that might indicate the presence of extraterrestrial intelligence.

The physics of the formation of the universe suggest that in the millions of galaxies with their billions of stars planetary systems may be the rule rather than the exception. The chemistry of the development of life on Earth, together with the discovery of organic molecules even in the depths of interstellar space, leads many scientists to consider the development of life on other planets as very likely.

The SETI program will search for life that has achieved intelligence and developed technology by looking in the quietest band of the electromagnetic spectrum (1000 to 100 000 MHz) for radio signals that may have leaked or been beamed from such highly developed civilizations on other planets. NASA's Ames Research Center will conduct a targeted search of stars like our Sun using the largest radio telescopes, including the one at Arecibo. The Jet Propulsion Laboratory will conduct a complementary survey of the other 99 percent of the sky, using the 34-meter-diameter telescopes in NASA's Deep Space Network. The SETI program is developing a spectrum analyzer that will sample millions of frequency channels looking for narrowband emissions that may be continuous or pulsed signals. Should such deliberately created signals be found, anthropologists will find ample work in interpreting the signaling culture to the receiving one and vice versa

With extraterrestrial contact rephrased in terms of radio communication only, it might seem that anthropologists and their skills would have little or no role to play in this grand intellectual venture—at least in terms of the common SETI scenario. That scenario envisages the reception of a purposefully transmitted signal containing some mathematical truth, physical constant, or other noncultural knowledge that would presumably be universally shared among intelligent species scientifically advanced enough to engage in radio communication. The next step in this scenario would be to build upon this universal knowledge to develop a common logical code or language—either through a patient and clever tutelage directed by the transmitting civilization or through a lengthy dialog across the gulf of however many light years might be involved (Freudenthal 1960). Signal processing experts, mathematicians, cognitive scientists, and linguists would seem the obvious specialists to participate in this radio contact process, not anthropologists.

However, it would be a mistake to assume that once a common code was shared, the rest of the task would be easy. Philip Morrison, whose joint paper with Giuseppe Cocconi (Cocconi and Morrison 1959) stimulated the SETI effort, wisely points out that a "complex signal will contain not mainly science and mathematics but mostly what we would call art and history" (Morrison 1973, p. 338). To decode such a signal would be difficult enough. To interpret the cultural material would call for an immense effort. Just think of the scholarship involved in deciphering the hieroglyphs and in reconstructing ancient Egyptian culture, even though the ancient Egyptians are of the same species as their modern investigators and in part culturally ancestral to them and even though they left the Rosetta Stone! (See figure 10.) Interpreting an extraterrestrial culture would be a never-ending task, which would generate a whole new scholarly industry, calling for the talents of specialists from all disciplines, especially anthropology. Anthropologists concerned about the disappearance of independent cultural entities on Earth should be among SETI's most ardent supporters. If the search is successful, anthropologists will have more than enough to do—for millennia to come.

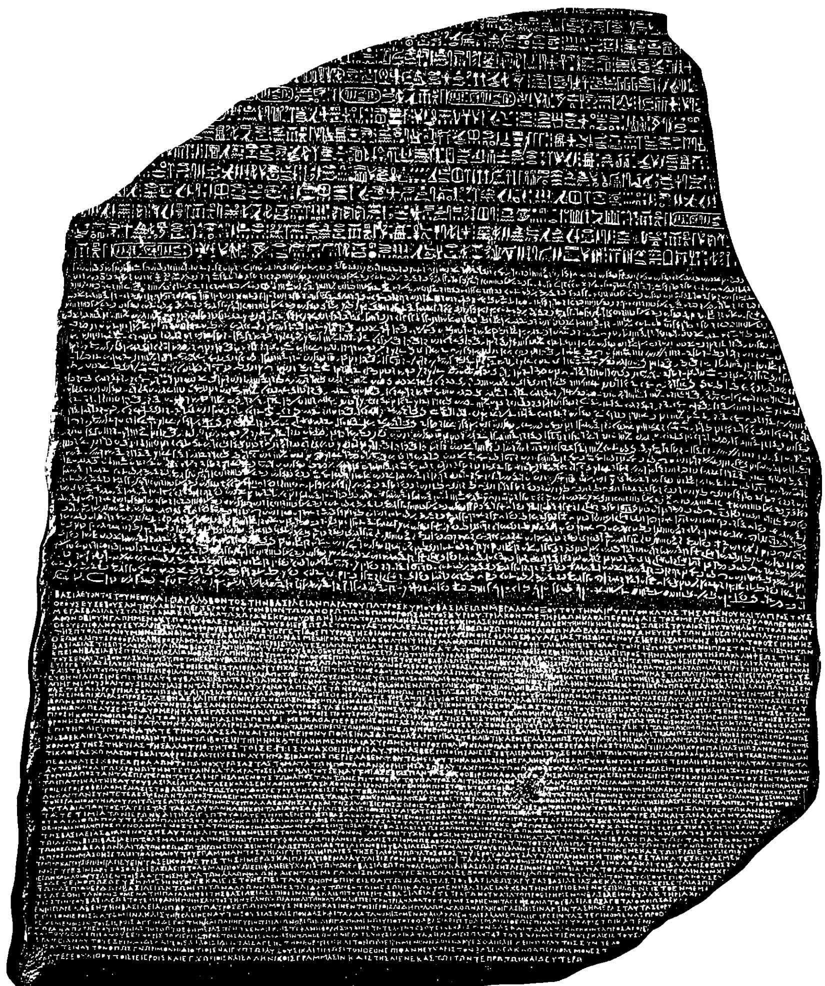


Figure 10

The Rosetta Stone

A slab of black basalt, rescued from demolition in A.D 1799 by a squad of Napoleon's troops in an Egyptian village called Rosetta, and containing a decree passed by a council of priests in 196 B.C., provided the key to the decipherment of Egyptian hieroglyphics.

The officer in charge of the squad, Lt. Pierre François Xavier Bouchard, is credited with having realized almost at once that the three inscriptions on the stone were versions of the same text. The content of the decree was soon known from a translation of the Greek capital letters in the bottom inscription. But the nature of the other two scripts—Egyptian hieroglyphics in the top portion and the cursive Egyptian script called demotic *which appears in the middle—was not fully understood until 1822. Neither form of Egyptian writing had been used for 1,370 years.*

A blocking misconception was the idea that, while hieroglyphics were merely pictorial, demotic was strictly phonetic. An English scientist turned linguist, Thomas Young, broke through this block and provided the link that the two Egyptian scripts were related through an intermediary script called hieratic *His translation of the demotic and the work of W. J. Bankes on the phonetic nature of royal names led French scholar Jean François Champollion to the conclusion that both Egyptian scripts on the Rosetta Stone contained symbolic* and *alphabetic elements. His knowledge of Coptic, the language of the Christian descendants of the ancient Egyptians, which was written in a sort of cross between Greek and demotic, helped him to finally decipher the Egyptian language in its most ancient script—hieroglyphics.*

And, of course, with knowledge of the language came a great increase in knowledge of the culture of the ancient Egyptians.

Explanation taken from Carol Andrews, 1981, "The Rosetta Stone," published by the British Museum.

Photograph reproduced by courtesy of the Trustees of the British Museum.

Even if we are the only intelligent species in the galaxy, or at least our corner of it, we might not be alone for long. If our own technology for settling space really works and enables some of our descendants to disperse throughout the solar system, a dramatic cultural rediversification of humankind would occur as the widely scattered colonies develop (through cultural drift or conscious choice) new ways of living. Then, if adventurous citizens of the solar system one day migrate to other star systems, their separation into small, self-contained breeding communities light years from their neighbors would virtually ensure biological speciation (Finney and Jones 1985). Earth-descended, though increasingly disparate, cultures and species would then be faced with the problem of understanding each other. Within such a galaxy of differentiating intelligent life forms, "astroanthropology" would be an essential tool for comprehending and relating to others beyond one's own cultural and biological experience.

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The Influence of Culture on Space Developments

Philip R. Harris

For a quarter of this 20th century, humankind has been successfully extending its presence into space. The landing of men on the Moon in 1969 during the Apollo 11 mission broke our perceptual blinders—we were no longer earthbound as our ancestors had thought for centuries. Perhaps the real home of the human species lies on the high frontier. Just as the application of fire and tools changed our primitive forebears, so space technology and its accomplishments force modern men and women to change their image of our species. We now are free to explore and use the universe to improve the quality of human existence. Our new self-concept as "Earth people" may energize global efforts toward space development. The technological achievements of NASA and other national space agencies, along with private-sector space undertakings, contribute mightily toward the actualization of our human potential. The exploration and exploitation of space resources are altering our human culture here on Earth.

Such vision is necessary to put the endeavors of space scientists and technologists into a larger context. During the past 25 years, the feats of people in the National Aeronautics and Space Administration and the allied aerospace industry have advanced human culture. The next steps of space technology into the 21st century will transform that culture.

Culture—A Coping Strategy

Culture is a unique human invention. Our species created it to increase our ability to cope with the environment, to facilitate daily living. Thus, consciously and unconsciously, groups transmit it to following generations. The concept of culture provides a useful tool for understanding human behavior and its relationship to a particular physical environment.

Human beings created culture, or their social environment, in the form of practices, customs, and traditions for survival and development. Culture is the lifestyle that a particular group of people passes along to their descendants. Often in the process, awareness of the origin of contributions to this fund of wisdom is lost. Subsequent generations are conditioned to accept these "truths" about accepted behavior in a society; norms, values, ethics, and taboos evolve. Culture is communicable knowledge which is both learned and unlearned, which is both overt and covert in practice, of which we may have either conscious or unconscious understanding. On this planet, human culture has been remarkable for its diversity, so that those who would operate successfully in an international arena have to learn skills for dealing effectively with cultural differences. The point is that culture is a powerful influence on human behavior as people adapt to unusual circumstances (Harris and Moran 1987).

The program manager for long-range studies at NASA's Office of Space Flight has listed some of the unusual circumstances on the high frontier that might influence the creation of a space culture: (1) weightlessness; (2) easy gravity control; (3) absence of atmosphere (unlimited high vacuum); (4) a comprehensive overview of the Earth's surface and atmosphere (for communication, observation, power transmission, etc.); (5) isolation from the Earth's biosphere (for hazardous processes); (6) an infinite natural reservoir for disposal of wastes and safe storage of radioactive products; (7) freely available light, heat, and power; (8) super-cold temperatures (infinite heat sink); (9) open areas for storage and structures; (10) a variety of non-diffuse (directed) types of radiation; (11) a magnetic field; (12) nonterrestrial raw materials; (13) absence of many Earth hazards (storms, floods, earthquakes, volcanoes, lightning, unpredictable temperatures and humidity, corrosion, pollution, etc.); (14) a potentially enjoyable, healthful, and stimulating environment for humans (Von Puttkamer 1985).

As the director of the California Space Institute, James R. Arnold, reminded us in a Los Angeles *Times* editorial (November 17, 1983), "Space is out there waiting for us to try out new ideas." In his view, the space station and other space bases to follow will give humans the time and place to learn, to experiment, to work, and even to play. In fact, the Soviets have already begun to do these things on their Mir space station. The formation of space culture has been under way now for over 25 years, and it is progressing rapidly.

Until now, only a handful of humans have actually lived in space. Whether Americans or Russians or their allies, these space pioneers were usually from a somewhat homogeneous background. Until the decade of the 80s, they came from subcultures like test pilots or the military and were mostly male. But, if we project to the next 25 years, it is obvious that the population in space will be increasingly multicultural and heterogeneous. Both Soviet and

American space flights, for example now include representatives of "allied" countries—cosmonauts or astronauts from "foreign" cultures. Just as on Earth there are human experiences that cut across most cultures, it would appear that living in space will become such a "cultural universal."

As we slowly extend our presence up there and establish human space communities in ever increasing numbers, there will be an urgent need for *cultural synergy*, be it on a space station or at a lunar base. Such synergy optimizes the differences between people, fosters cooperation, and directs energy toward goals and problem-solving in collaboration with others (Moran and Harris 1982). The very complexity of transporting people into space has stimulated the development of matrix or team management in the space program. Similarly, the creation of space habitats and colonies in a zero- or low-gravity environment will require synergistic strategies of leadership.

Current research in evolution indicates that harsh environments often result in innovation by species. The pattern of the past reveals that creatures are better at inventing and surviving when challenged by a difficult environment than they are when not challenged (Harrison and Connors 1984). The big jumps in species development seem to occur under such circumstances. Perhaps this will be true of the human race as we shift our attention from Earth-based to space-based resources. As the Apollo missions demonstrated, the very size, scope, and complexity of a space undertaking may be the catalyst for unleashing our potential and raising our culture to a new level. This may be the first time in human history that people can consciously design the kind of culture they wish to create in an alien environment slated for exploration and exploitation. The movement of people from their home planet to the "high ground" will transform both our culture and the human person. The editors of *Interstellar Migration and the Human Experience* remind us that "Migration into space may be a revolutionary step for humanity, but it is one that represents a continuity with our past" (Finney and Jones 1985).

Space planners can benefit immensely by utilizing the data base and insights of behavioral scientists (Connors, Harrison, and Akins 1985). Cultural anthropologists, for instance, offer a variety of approaches to cultural analysis. One method is called a systems analysis; here "systems" refers to an ordered assemblage of parts which form a whole. Thus, in planning space communities, one might utilize eight or more systems, such as illustrated in figure 11. That is, the new space culture can be studied in terms of systems that are used to indicate relationships—for association, or social grouping; for economic and political purposes; for education and training; for health and recreation; for leadership and guidance (this last being the transcendent or philosophical system around which the space community might be organized). In *Living Systems* (1978), James Grier Miller has proposed a master paradigm for integration of both biological and social systems. Dr. Miller is currently engaged in research to apply his eight-level conceptualization of twenty subsystems to analysis of the cultural needs of future space communities (see his paper in this volume).

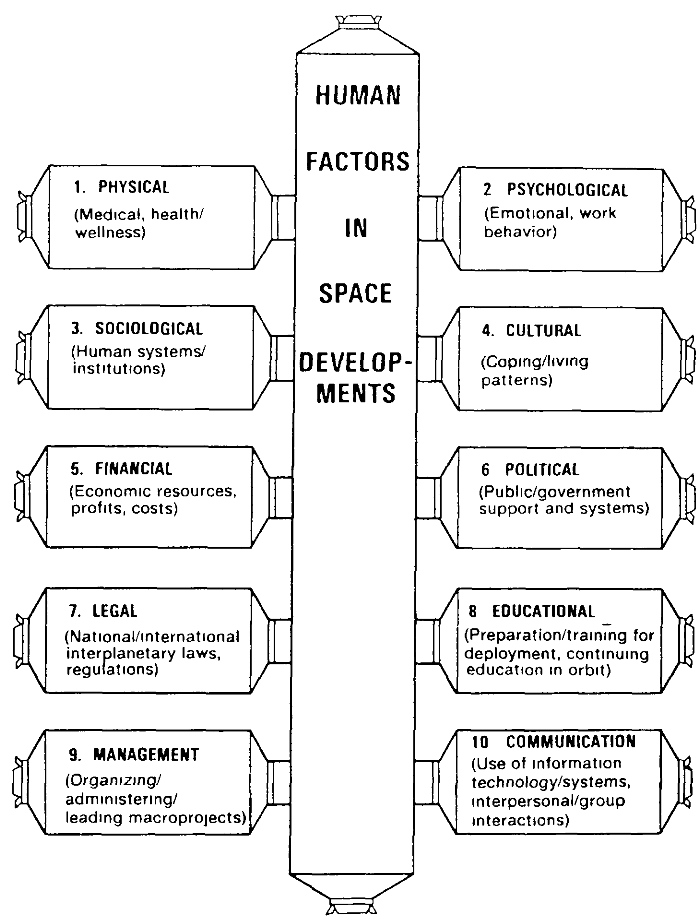

Figure 11

Systems for Analysis of a New Space Culture

Another way of preparing for a new cultural experience is by examining typical characteristics of culture. Some of these for a space community might be the following:

(1) Sense of self

(2) Communication

(3) Dress

(4) Food

(5) Time consciousness

(6) Relationships

(7) Values

(8) Beliefs

(9) Mental processes

(10) Work habits

These ten classes offer a simple model not only for assessing an existing culture but also for planning a new one, such as a culture in space. Although there are other characteristics for cultural analysis (such as rewards), analysis of the listed characteristics would be sufficient to prepare for a startup space community, such as that of the crew at a space station or a lunar outpost.

Because culture is so multifaceted and pervasive in human behavior, we cannot simply impose one form of Earth culture on a space community. Nor can space technologists continue to ignore the implications of culture (Hall 1985). If the space population is to be increased and broadened, so should the composition of space planners and decision-makers (as happened in miniature with the multidisciplinary group of participants at the 1984 NASA summer study at the California Space Institute.)

Organizational Culture in NASA and the Aerospace Industry

Culture has already unconsciously affected our future in space through the organizational cultures of the chief developers of space technology. A distinctive culture has emerged in the past 25 years within NASA itself, and this in turn has influenced the corporate cultures of NASA's principal contractors. NASA has been an atypical government agency that has been innovative in both technology and management, as well as in its relations with contractors (Harris 1985).

When NASA was established as a civilian Government entity in 1958, it inherited cultural biases from the several organizations from which it was derived. It acquired many of the traditional characteristics of Federal public administration, being subject to the constraints of Civil Service regulations, annual budget battles, congressional and lobby pressures, and changing public opinion (Levine 1982). Since it was chartered to be mainly a research and development organization, NASA was dominated by the subcultures of the scientific, technological, and engineering fields. Its interface with the military and its astronaut personnel from the Armed Forces provided another stream of cultural influence. The introduction of the German rocket specialists under Wernher von Braun provided further cultural input, as have numerous academics and their universities, beginning with Robert Goddard of Clarke University and coming right down to participants in the latest NASA summer study on the campus of the University of California, San Diego.

Currently, the organizational culture of NASA is being altered by its interactions with other national space agencies, such as those of Japan and Europe, and even by its successful cooperation with the Soviets in the Apollo/Soyuz mission. To broaden its constituency further, NASA is attempting to reach out to nonaerospace business and involve companies in space industrialization; to expand its cooperative efforts with other Government departments, from weather and transportation to commerce and defense; to engage in joint endeavors with national academies and associations, such as the American Institute of Aeronautics and Astronautics (AIAA). The ongoing history of NASA manifests continuing alterations of its culture from crises (e.g., the *Challenger* disaster) and reactions (e.g., congressional investigations) and new inputs from Presidential commissions (e.g., the Rogers Commission report, 1986).

Just as groups of people develop national or macrocultures, so too do human institutions develop organizational or microcultures. NASA as an organization is a collection of humans who have set for this system objectives, missions, expectations, obligations, and roles. It has a unique culture which is influencing the course of space development. The NASA culture begins by setting organizational boundaries and powerfully affects the morale, performance, and productivity of its employees. Eventually, this influence spreads to contractors and suppliers. For example, as NASA began to plan for its next 25 years, Administrator James Beggs circulated a statement of goals and objectives to administrators and center directors. This statement from the first item enunciated demonstrates a future trend in NASA culture:

GOAL: Provide our people a creative environment and the best of facilities, support services, and management support so they can perform with excellence NASA's research, development, mission, and operational responsibilities.

(*Government Executive*, October 1983, p. 5)

To analyze this NASA culture, one can take the ten characteristics listed in the previous section or one can use a diagnostic instrument (see "Organizational Culture Survey Instrument," appendix A in Harris 1983). Perhaps figure 12 best illustrates the possible dimensions of this NASA culture.

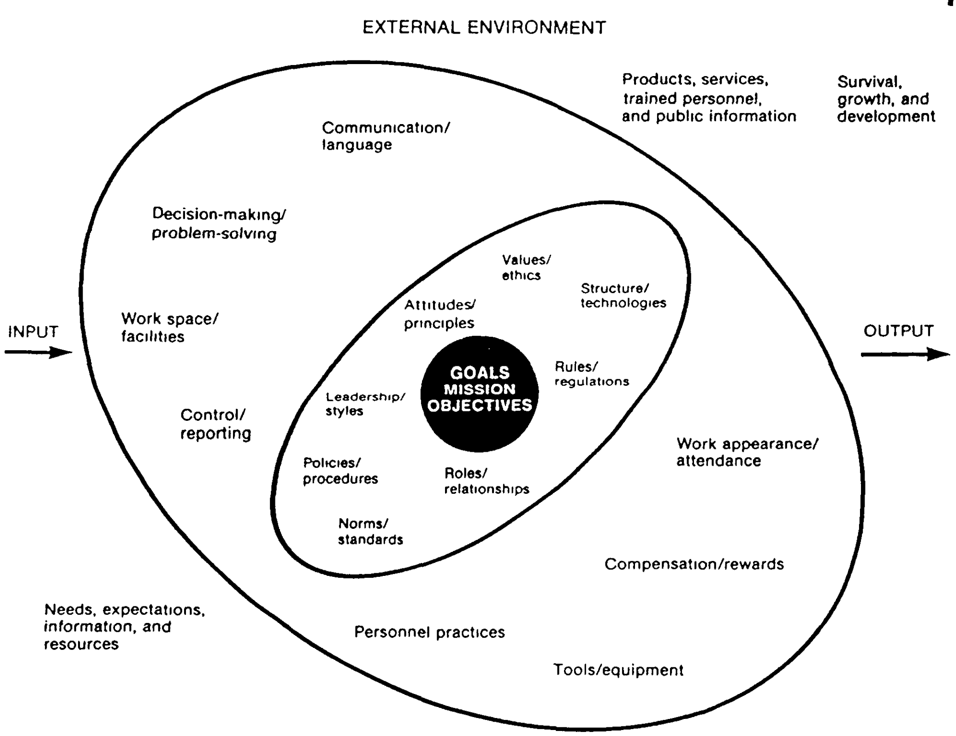

Figure 12

Aspects of NASA's Organizational Culture

The fact that NASA successfully completed its Apollo lunar missions would seem to indicate that its organizational culture was adequate. Since then, budget cuts, loss of talented personnel, and the *Challenger* accident have pointed up the need for cultural renewal. In 1986, as a result of the report of The Presidential Commission on the Space Shuttle Challenger Accident, reorganization got under way following the appointment, once again, of James C. Fletcher as NASA Administrator.

The issue of concern now is whether the agency's cultural focus will enable NASA to provide global leadership in the peaceful and commercial development of space. As NASA struggles with "organization shock," external forces demand that priority be given to military and scientific missions, leaving commercial satellite launchings and industrialization to the private sector. Other international space agencies—in Europe, Japan, and even the Third World—compete with NASA in launch capability. Confusion reigns over replacement of the fourth orbiter, development of alternative launch capability, and space station plans, so that NASA is an organization in profound transition, requiring transformational leadership (Tichy and Devanna 1986). This is especially true if NASA is to implement the vision outlined by the National Commission on Space (1986) in its bold report, *Pioneering the Space Frontier*.

As an example of the way NASA culture affects its space planning and management, consider the well-documented fact that the agency is leery of the behavioral sciences (Harrison 1986, Hall 1985, Douglas 1984). Since the organization is dominated by a technical mindset, it is uncomfortable with social scientists and their potential contributions. And yet the agency culture changes, as witnessed by the publication of the June 1988 report of the NASA Life Sciences Strategic Planning Study Committee, entitled *Exploring the Living Universe: A Strategy for Space Life Sciences*, and by requests for increased spending on the behavioral sciences in the FY89 budget.

As human presence in space is expanded with long-duration missions, NASA planners will have to confront issues of interpersonal and group living which until recently they avoided (Connors, Harrison, and Akins 1985). In interviews by flight surgeon Douglas (1984) with astronauts, the latter expressed regrets that they and their families did not benefit more from the services of psychiatrists and psychologists, particularly with reference to group dynamics training. Oberg (1985) reveals that, on the other hand, in the culture of their space program, the Soviets are more prone to utilize such specialists. In fact, that author quotes the Soviet head of space biomedicine, Dr. Oleg Gazenko, as stating that the limitations to human living in space are not physical but psychological (p. 25); Oberg also notes that Svetlana Savitskaya, the second woman in space, suggested that a psychologist be included on long-duration flights to observe firsthand the individual stress and group dynamics (p. 32).

My purpose here is simply to bring to the reader's consciousness the reality that NASA does have a culture and that that culture pervades its decisions, plans, operations, and activities. One might even take the chapter headings of the volume *Corporate Cultures* and use them to assess NASA's values, heroes, rites and rituals, communications, and tribes (Deal and Kennedy 1982).

As reported in a variety of contemporary management books, from the one just mentioned to *In Search of Excellence*, research supports the conclusion that excellent organizations have strong functional cultures. Since its founding, NASA surely has created its share of space leaders, legends, myths, beliefs, symbols, visions, and goals—the stuff of meaningful organizational cultures. But, as Peters and Waterman reminded us,

> In the very institutions in which culture is so dominant, the highest levels of true autonomy occur. The culture regulates rigorously the few variables that do count, and provides meaning. But within those qualitative values (and in almost all other dimensions), people are encouraged to stick out, to innovate.
>
> (Peters and Waterman 1982)

Thus, if NASA is to provide the world with the technological springboard into the 21st century, these questions are in order:

(1) Does NASA now have the necessary innovative and entrepreneurial culture to provide leadership for its own renewal and the enormous human expansion into space? Or is it trapped inside both bureaucratic and technical cultures that inhibit its contributions to the next stage of space development?

(2) Has NASA adequately redefined and projected its present organizational image and purpose to its own personnel, the Congress, and the public at large? Or is it suffering again (as it did after three astronauts were killed in the Apollo capsule fire) from an identity crisis and a dysfunctional culture?

As NASA moves beyond its institutional beginnings into the next stage of organizational development, maturation would seem to require transformation. Perhaps the present structure is no longer suitable for this growth process and it needs to become a more autonomous agency. (Does the Tennessee Valley Authority provide a model for this structural change?) Perhaps it should be part of a global space agency that represents both public and private space interests—first in the free-enterprise nations and someday even in the Communist bloc. Perhaps NASA needs to enter into new relationships and ventures with contractors, whether in the aerospace industry or in other multinational industries.

It was encouraging to know that the 1984 NASA administrator advocated decentralization in the organization, putting operational responsibility at the center level. However, in 1986 the trend was being reversed with demand for strong headquarters management and inauguration of a new technical management information system. To meet the space challenges of the future, NASA would do well to consider planned changes in its own organizational culture. Technological, economic, political, and social changes by 2010 will demand such adjustments, and many present organizational structures, roles, operations, and arrangements (such as a centralized mission control) will be obsolete.

Emergence of a New Space Culture

The habitation of Skylab, Spacelab, Salyut, and Mir by a few dozen humans is the precedent not only for space station life but also for space culture. Whether astronauts or cosmonauts, they were humans learning to cope with a new environment marked by a lack of gravity. For most, it appears to have been an enjoyable experience, despite minor inconveniences caused by space sickness or excessive demands from experiment controllers on the ground. Whether inside or outside the space suits and capsules, these people learned to adapt and they proved that human life in space is possible, even practical. These innovators simply transported into space the macroculture of the country that sponsored their space voyage. The U.S. astronauts reflected American culture, while their Soviet counterparts carried Russian culture into these prototypes of future space communities.

In the decade of the 1990s, the duration of missions and the number of humans in space will increase as more permanent types of space stations are constructed in orbit and expanded in size. Perhaps the Americans will name these initial space communities after their space pioneers and heroes, like Goddard, Von Braun, and Armstrong; while the Russians may name theirs after space luminaries like Tsiolkovsky, Korolev, and Gagarin. Then the real challenge of creating a new space culture will get under way. A major human activity of the 21st century will be the building of space communities. Already, Rep. George Brown (D—Calif.) has a bill pending before the U.S. Congress that would authorize NASA to provide leadership in space settlements.

The issue for consideration now is whether this process will be planned or unplanned. In the United States, for example, there exists a whole body of literature and research in cultural anthropology that could be most useful in the design of a space culture. Anthropologists are beginning to probe this new reality and to look for insights their field can contribute (see Finney's paper in this volume). Will NASA, for example, use the nation's anthropologists in the planning of a lunar base? If the human composition of that enterprise is to be multicultural, as is likely, will the agency call on international experts in cross-cultural psychology and anthropology? Perhaps NASA should join with its colleagues in the Japanese and European space agencies in sponsoring a summer study of behavioral scientists to address matters related to the emerging space culture.

Space gives us an opportunity to establish a living laboratory to promote peaceful international relations. For example, suppose the sponsors of a particular space station or base were to have as a goal the establishment of a synergistic society on the high frontier. Anthropologist Ruth Benedict and psychologist Abraham Maslow have already provided us with a glimpse of human behavior under such circumstances. Imagine a space community in which the cultural norms supported collaboration and cooperation rather than excessive individualism and competition. Consider space colonists who are selected because they demonstrate high synergy—that is, because they are nonaggressive and seek what is mutually advantageous; they encourage both individual and group development; they operate on a win/win philosophy, or aim for group success; they share and work together for the common good. Such considerations take on special relevance in light of proposals for a joint U.S.A./U.S.S.R. mission to Mars. A space culture that espouses synergy might have a better chance for survival and development than one that did not. We should have learned something from the debacle of Fort Raleigh in 1594, the first "lost colony" of our English forebears.

Since culture formation seemingly occurs in response to the physical environment, consider briefly the situation faced by those seeking to establish the first permanent community on the Moon, a base from which we can explore other planets in the universe. It is a remote, alien environment. The long-term inhabitants would have to adapt their culture to cope with isolation, for they would be a quarter of a million miles away from home, family, and friends on Earth. The physical realities of life on the Moon would force its inhabitants to adapt their earthbound culture (Pitts 1985). Remember, the Moon lacks atmosphere, there is no weather there, and there are various kinds of radiation which require protective cover.

Back in 1969, astronauts Armstrong and Aldrin confirmed that the lunar surface was firm and could support massive weight. During the last visit to the Moon, Apollo 17, the first professional scientist on these missions, Dr. Harrison Schmitt, conducted geological studies, so we now have some idea of the composition of this body. But there is much we still do not know about the Moon, such as the nature of its poles and whether any of its craters were formed volcanically.

Before the turn of this century, it would seem advisable for NASA to follow a Soviet lead and undertake automated missions to gather lunar data if we are to plan adequately for the new space culture on the Moon's surface. At NASA's Johnson Space Center, scientists have a scheme for cultural expansion which begins with precursor exploration in a 1990-92 timeframe (Duke, Mendell, and Roberts 1985). It would require new technology development to exploit lunar resources and define the site for a research outpost and lunar base. The first two phases of site development would rely on automated and cybernated systems. In the third phase, permanent human occupancy by a small group of "astrotechnicians" is projected; then, in the fourth phase, an advanced base with more people would result, possibly by the year 2010.

To illustrate why serious preparations for a Moon base should include studies of space culture by social scientists, let us view figure 13 in the context of a lunar base.

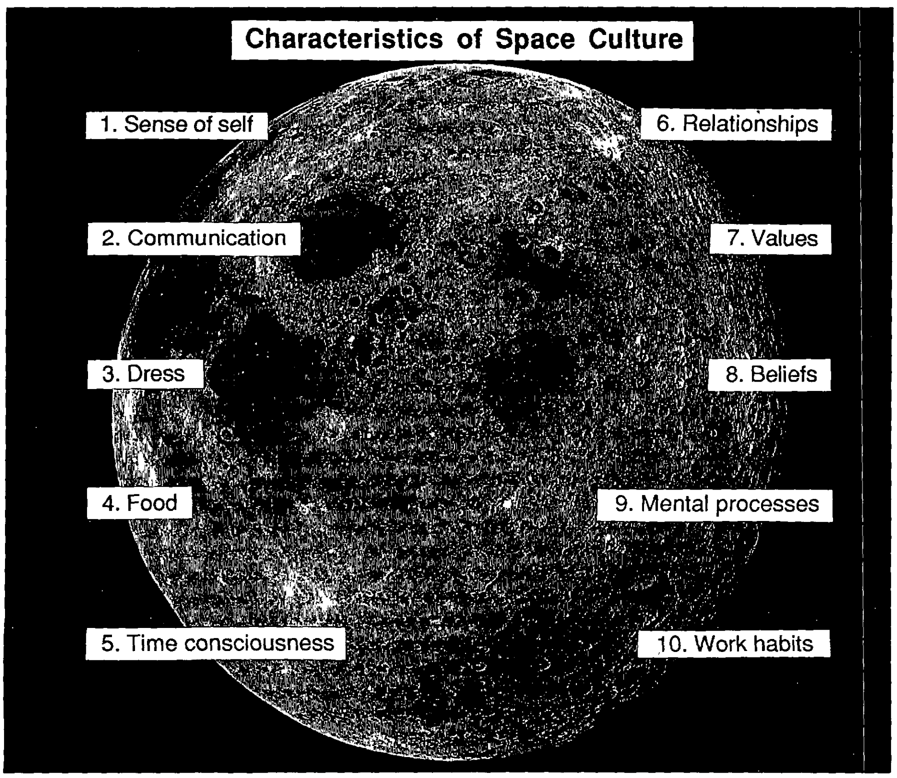

Figure 13

Characteristics of Space Culture

1. Sense of Self

Self-identity and self-acceptance are manifested differently in different cultures. The comfort we feel with ourselves and others, the physical or psychological space we maintain between ourselves and others—these are products of culture. For an international crew on a space station, as an example, there would be differing needs for privacy or personal space. One can speculate as to whether an international community on the Moon should, for the purpose of fostering such comfort, be structured as an open or a closed society. Personally, I would recommend an open, friendly, informal, and supportive community, such as expatriates often maintain among themselves when far away from their mother country. (Though the society of expatriates may be seen as closed to the surrounding society on Earth, such a perspective would be irrelevant in space where humans are alone.)

The space culture to emerge will validate individuals in new ways. First, there are the realities of no atmosphere and 1/6 gravity—certain to lead to interesting adaptations. With so much space and so few people, rugged individuals may develop (like the mountain men on the early Western frontier) or humans may learn to become more interdependent. Just as the American Great Plains affected the perspective of its inhabitants, so will the vast views of the universe affect lunar dwellers. Considering the confined quarters in the early stages, will the first colonists be ambivalent in behavior because of the difference between their sense of interior space and that of exterior space? Also, what happens to lunar colonists when they return to Earth after several years on that other sphere? Having been accustomed to Moon weight, they will on return to Earth feel heavier than lead, and their whole sense of self will require profound readjustment.

2. Communication

Much of our terminology may be inappropriate for the lunar experience. In space, we will need a new vocabulary to replace "up and down" and "day and night." Back in 1957, when German space science professor Hermann Oberth wrote his classic *Man Into Space*, he reminded us that we would have to change our ideas about construction, because "other laws prevail in space and there is no reason why the old architectural rules should be followed." By extension and analogy, our language about construction and indeed most other subjects will have to change in a drastically different environment.

Will there be one official language or several in use? If the first crews and settlers are international in makeup, is English to be preferred or should all be fluent in two languages? (If Americans were to undertake a joint mission to Mars with the Soviets, for instance, then both English and Russian would probably be required.)

Certainly, we can expect extensive use of computers and satellites for communication, but what will be the procedures and the pattern of interactions between humans on the Earth and on the Moon, and how will the means of communication affect the cultural expansion?

3. Dress

Culture is also expressed in garments and adornments. We may or may not want uniforms with mission patches, but lunar conditions will dictate certain types of clothing or space suits. They will have to be designed to serve a variety of purposes from protection to comfort. In 1984, for example, the first female to walk in space, cosmonaut Svetlana Savitskaya, commented that her space suit was not elastic enough and that she had to expend too much energy for each movement (Oberg 1981).

Some scientists have described the Moon as an impossible environment for humans, but so was the Earth for the first living things there— they coped by staying in the sea for the first two billion years! Humans will adapt to lunar conditions which require them to wear life support systems when they leave their protective habitats. That necessity will be incorporated into the new culture, and it will alter behavior from that on Earth. Dr. David Criswell, director of the Consortium for Space and Terrestrial Automation and Robotics (C-STAR), believes that astronauts in space suits are like disabled or handicapped persons, and that space planners could learn much from the field of rehabilitative medicine (1988).

Twenty-first century clothing styles on the home planet may be very much influenced by styles that develop for the lunar surface or for interstellar travel. Explorers and scientists in the Antarctic have tended to grow beards and longer hair. We wonder what lunar dwellers will do. Perhaps they'll shave off all their hair to keep from having to tuck it into their space suits every time they don them.

4. Food

The diet and eating procedures of a group of people set it apart from other groups. We are all aware of NASA's pioneering in food technologies and compositions, so that even our own intake here on Earth has been altered by the astronaut experience. However, because of transportation costs, we will have to cut back on the amount and type of food cargo from Earth and depend on new closed biological systems to provide human sustenance. Hydroponic farming, featuring plants suspended in nets above circulating liquids that provide nutrients, may prove a boon. With traditional foodstuffs at a premium, the new culture may focus on high-quality and high-energy nourishment, thereby affecting the breed of both humans and other animals in space.

Although the lunar cuisine may not be as pleasant as that of the mining camps in the Old West, its preparation, presentation, and eating will surely alter the culture. One certainty is that food packages will not be disposable but rather recyclable. Let us hope habitat planners make up somewhat for the rations and regimen by providing a view of the Earth in the dining and drinking area. Or will there be any views from these modules buried in lunar regolith for protection from radiation?

5. Time Consciousness

The sense of time differs by culture, and yet lunar inhabitants will have to keep in touch with mission control. Will the 24-hour time system prevail on the high frontier? Or will the exact sense of time gradually be replaced by a relative one, like that of traditional farmers who go by sunrise and sunset and seasonal changes?

That particular time sense would of course have a different expression on the lunar surface, where the "day" lasts for 2 weeks and so does the "night." Because the axis of the Moon does not tilt as does the axis of the Earth, the Moon lacks seasons. Will the long periods of darkness and isolation incline the first Moon colonists toward suicide, as NATO has found its soldiers posted in northern countries to be? Will they suffer with manic behavior, as some Swedes do after their annual dark periods? If one needed change, one could move around the Moon from areas of darkness to areas of light. But what will happen to the whole concept of day and year, so much a part of the human heritage?

6. Relationships

Cultures fix human and organizational relationships by age, sex, and degree of kinship, as well as by wealth, power, and wisdom. The first lunar inhabitants are likely to establish relationships on the basis of professionalism or their respective disciplines. They will be scientists and technicians, civilian and military. Theirs will be primarily work or organizational relationships, even if they are of different nationalities. Because the first colonists will be knowledge workers (that is, people who work with information and ideas), there is likely to be comparative social equality among them. Eventually, the founders will gain special status in the community.

The first element to alter the arrangement will be male-female relations. Eventually, this will lead to the first pregnancy on the lunar surface. As more and more people go to the Moon, there will be legal and illegal liaisons and eventually children will be born on the Moon, and someday on Mars. Dr. Angel Colon of Georgetown University Medical School has already anticipated the situation with his research on space pediatrics.* The point is that space will be a whole new ball game in terms of human relationships and a culture will grow in response to such new realities.

New familial arrangements will emerge (Oberg and Oberg 1986). It remains to be seen whether monogamy, polygamy, or polyandry will become the norm in 21st century space communities. If the first lunar colonists are only males, homosexuality may become prevalent; whereas, if mixed groups are sent, then heterosexuality will be the basis for many relationships. Astronaut Michael Collins (1988) proposes that six married couples be selected for any manned mission to Mars.

Should the makeup of the first crew be purely civilian, then we could expect one lifestyle; whereas, if military people are included, then we would expect another lifestyle including rank and protocol. The issue of such relationships will affect governance, housing assignments, and social life.

Another unique feature of space culture will be human-machine relationships. Automation will dominate not only the transportation system but also the exploration and life support processes (Freitas and Gilbreath 1980, Automation and Robotics Panel 1985). Humans may form new attachments to their helpers, especially as designers program more humanlike capabilities and features into these extensions of ourselves. Inventive applications of artificial intelligence on the Moon may not only facilitate functions in lunar communities but also serve as tests of expert systems, which may then be transferred to Earth. Knowledge engineering will accelerate as a result of space development, and space culture will feature teleknowledge (information developed by technical transmission) and telepresence.

*Personal communication.

7. Values

The need system of the space culture will be unique, and out of it will evolve special priorities to ensure survival and development. In time, these priorities will form the value system of the lunar base. As the colonists move up on the hierarchy of needs, their values will change. The resulting value system will in turn influence the norms or standards of the lunar community—that is, acceptable behavior in that situation. It is these mutual premises that will determine whether the colonists are pleased, annoyed, or embarrassed by the conduct of their fellows. Eventually, this process will produce conventions that are passed along to each new group of lunar settlers, so that the preferred practices of privacy, deference, etiquette, and gift-giving will be established.

For example, it is conceivable that these lunar pioneers may ban all talk of Earth accomplishments, happenings, or experience and focus only on what is done on the Moon or in space. They may learn to value the people on the space station, who supply them, more than remote people on the home planet, even when they represent the government. Because of their unusual view of the cosmos and the light/dark situation on the Moon, they may value artists more highly than technicians, for their capacity to express the pioneers' feelings and longings.

At the 1974 Princeton Conference on Space Colonization, Richard Falk examined "New Options for Self-Government in Space Habitats." He proposed four shared commitments that would enhance space living: (1) to the minimization of violence, (2) to economic well-being for all settlers in the habitat, (3) to a guaranteed level of social and political justice, and (4) to the maintenance and improvement of ecological quality (1977). Falk's premise is that this sort of value consensus before settlement would influence recruitment and selection of space personnel, as well as provide an ethical orientation for their training.

8. Beliefs

People's lives, attitudes, and behavior are motivated by spiritual themes and patterns which may take the form of philosophy, religion, or transcendental convictions. If the population of a lunar community is international, the space culture emerging on the Moon might include beliefs from the Earth's religious traditions—primarily Judaism, Christianity, Islam, Hinduism, Buddhism, and even Confucianism. However, since such belief systems are also reflections of new stages in human development, space dwellers may create their own unique form of "cosmic consciousness" that raises the human race to a new level of being and perceives the oneness of the human family. For example, suppose a space colony were developed on the basis of a belief in synergy; the members would then be dedicated to creating a synergistic society through cooperation.

9. Mental Processes

The way people think and learn varies by culture because of different emphasis on brain development and education. Space culture, for instance, may offer humanity a rare opportunity to focus on whole, not split, brain development. Obviously, modern communication technology and satellites will have a primary position in information sharing and knowledge development. For education and training, the first lunar colonists will rely on computers and a data bank, as well as on a variety of modern media alternatives. Self-instructional systems will be widely employed, and all in the group will be expected to share their expertise and competencies with each other as circumstances require.

Assuming that a multicultural community develops, a synergy may emerge between Eastern and Western cultural orientations to learning, so that an integration of logic, conceptualization, abstract thinking, and intuition may evolve. We can anticipate a new reasoning process being created in space, especially with wider applications of artificial intelligence. With the removal of many ground-based blinders and binders, the creative process may be unleashed and human potential actualized.

10. Work Habits

One way of analyzing a culture is to examine how the society produces its goods and services and conducts its economic affairs. The work culture in space will be metaindustrial and will feature the use of high technology. In the beginning, the work will be performed outside using cumbersome space suits to provide life support. Or it will be done by robots, operating automatically or under the manual guidance of humans, who may remain in a protected habitat. On the surface of the Moon, for instance, this work may involve the mining, transportation and distribution, and processing of lunar materials.

Human vocational activity will include the operation and repair of communication satellites, the creation of solar power stations, and the conversion of solar power into microwaves for transmission to Earth and subsequent reconversion to electricity. The first space stations, as well as bases on the Moon, and subsequently on Mars, will involve much construction—using new space materials and designs to build habitats and factories, communication and storage facilities, and other necessary structures.

The early space workers will focus on the transformation of nonterrestrial resources into useful supplies, such as oxygen, water, and cement. The nonterrestrial workers will use zero or low gravity to facilitate their labor, and they will take advantage of the vacuum. All of this work will require extensive use of computers and automation, and the "tin collar worker," or robot, will be a principal ally.

Such unusual work activities will influence the direction of the culture. The roles of knowledge workers and technical workers will probably be enhanced. Since those who get into the first space communities are likely to be highly selected, competence in one's field of expertise and multiskillfulness are norms that will probably emerge. The space culture will reflect these worklife changes in art and artifacts as well as in technology.

The new space enterprises and the culture thus created are a fruitful arena for social science research. Furthermore, these developments will have enormous impact on Earth-based work cultures. Large American corporations, from Fairchild and McDonnell Douglas to General Dynamics and Rockwell, are already gearing up for construction of the $8 billion space station, the staging area for exploration of the rest of the solar system. It may very well develop as a multinational facility for spacefaring peoples—a foretaste of 21st century life and culture.

Space Personnel Deployment System

The movement of large numbers of people from their native country to a foreign one has spurred increasing interest, especially on the part of transnational corporations, in the phenomena of culture shock and reentry shock. When people are rapidly transported from their home culture to a strange environment abroad, they may experience severe disorientation, confusion, and anxiety. Their sense of identity is threatened when they are removed from the comfortable and familiar and thrust into the uncertain and unknown. Such expatriates, particularly overseas managers and technicians who may be away from home for many months or years, go through a transitional experience that may include such phases as growing awareness of differences, rage, introspection, and integration.

Many multinational businesses have relocation services, as well as cross-cultural orientation and training programs, to facilitate acculturation of personnel to the new environment with its changes and challenges. In a previous publication, I have proposed that various aspects of foreign deployment support services be systematized (Harris and Moran 1987). Such an approach could be adapted for Earth people going into space to establish first construction bases and then planned communities. Figure 14 depicts my conception of a space personnel deployment system.

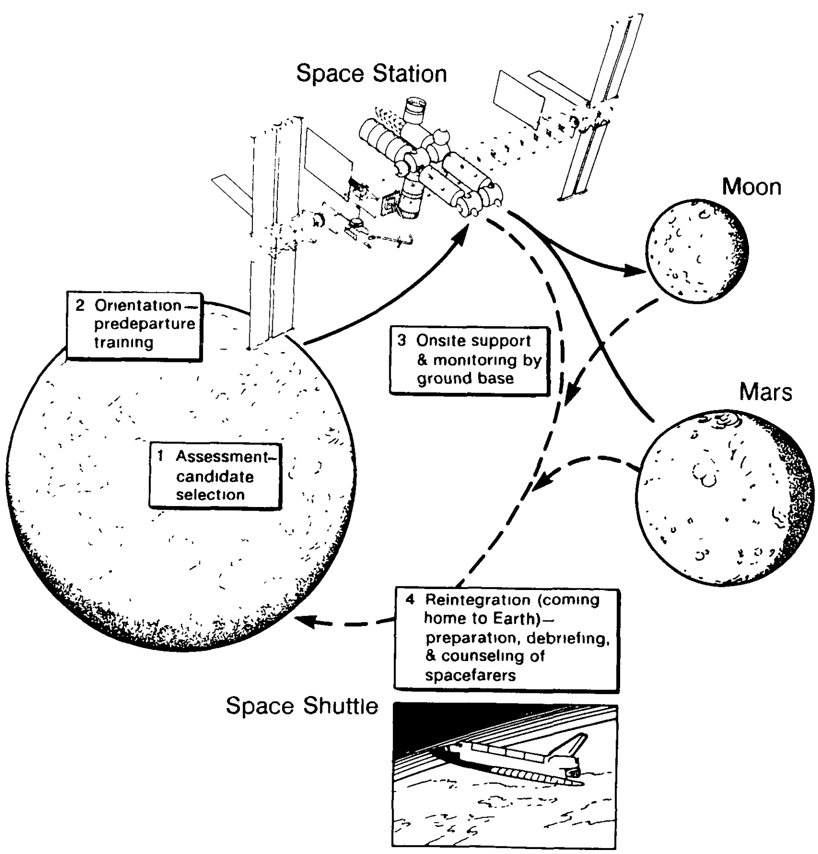

Figure 14

A Space Personnel Deployment System

At the moment, it is unlikely that spacefarers will have to deal with extraterrestrial "foreigners" — but they will have to cope with all the other aspects of adaptation to a new cultural environment. Research by Harrison and Connors (1984) on groups in *exotic environments* is relevant. Their "exotic environments" include polar camps, submarines, offshore oil rigs, space capsules — any isolated and remote living situation. Such experiences can assist in planning life in space stations and settlements.

We can thus prevent or limit the psychological "shock" of isolation, loneliness, and strangeness that humans may experience when living on the high frontier for many months or even years. The following outline of a system for intercultural preparation and evaluation is proposed for further research by NASA. It could avoid or reduce the depression, withdrawal, hostility, paranoia, and other mental health problems that may afflict space travelers, and thus it could contribute to mission success.

1. Assessment

In the next decades of space development, sponsoring organizations should take care in the selection of space settlers, workers, and travelers. Whether the group is a national space agency, an aerospace contractor, a commercial enterprise, a government department, a media company, or a tourist firm, it should be responsible for the spacefarer's well-being, as well as the impact of that person on the space community. Better to screen out potential misfits than to attempt to provide care and rehabilitation in space. The rigorous and defined selection and training used for NASA astronauts may not be the basis for future space deployment; these guidelines would seem advisable as a more diverse space population evolves:

- WHAT—Ascertain the ability of each space candidate to adapt to and deal effectively with the new environment, evaluate both the physiological and the psychological capability of the individual to deal with the difficulties and differences of long space travel and of life in space under constrained conditions, identify proneness to space culture shock and areas for retraining to improve adjustment to space conditions, ascertain needs for skills in human relations and coping.

- WHO—Apply such screening of space travelers and settlers to all who would utilize Government transportation, whether NASA personnel, contract workers, visiting professionals, members of the Armed Forces or Congress, visiting dignitaries from any source, representatives of the media, tourists, or the families who accompany any of these people to a space station or base.

- HOW—Use a variety of means to evaluate suitability for space living, such as psychological interviews, questionnaires, tests, simulations, and group meetings.

- WHY—Seek not only to determine suitability but also to identify those requiring preventive counseling because of their likelihood to experience space culture shock. The aim is to eliminate from space communities, at least in their founding stages, those who would want to return to Earth prematurely, those who would be disruptive influences in a space colony, and those who would simply not be satisfactory for their space assignments. Initially, the cost of transporting people to and from space will demand a careful selection policy and program.

NASA should consider establishing an organizational data bank on human factors to be used in the selection and preparation of spacefarers. Such a data bank might include information from research on personnel living in such exotic environments as submarines or the scientific bases in Antarctica. It might contain information on space habitat conditions and lifestyle, including data on food, medical conditions, responses to weightlessness, and skills required. Eventually, as experience in space living increases, the data bank might include specific cultural information for space stations in orbit, lunar bases, martian bases, and similar locations in space. Space "expatriates" while onsite or upon return to Earth would be asked to contribute insights to this fund of knowledge about life in zero or low gravity. Eventually, such input could be classified by the orbit in which the experience was garnered.

In time, this data bank about space life may become the basis of policy and guidelines for space travel which would be formulated by government agencies, corporations, or other organizational sponsors of people in space. It may someday contribute to practical decisions about such interplanetary matters as laws and insurance, passports and visas, financial compensation and allowances, taxes, security, training, and suitable dress.

In selecting the first space workers for a tour of duty of 12 months or less, practicality may give preference to those healthy and well-balanced persons who (a) have already had astronaut training, (b) come as a happily married couple with complementary competencies, and (c) are committed to long-term living in space.

Undoubtedly, NASA has already assembled a wide range of data about the performance and needs of astronauts in space during the past 25 years. In the next quarter century, we expect that a more heterogeneous population will be going into space. Research should be funded on the dimensions for successful space adaptation. Eventually, a profile, useful for assessment, could be developed of requirements in space for technical competence, resourcefulness, creativity, productivity, adaptability, emotional stability, motivation, risk-taking, interpersonal and communication skills, leadership and growth potential, cultural empathy, and other psychological, as well as physical, attributes.

We should take advantage of this period before the time of mass travel into space to conduct research on and develop means of coping with that alien, sometimes hostile, zero- or reduced-gravity environment. The pioneers who experience space life in the next 25 years can provide insight into the new culture and information on adjusting to it. Their Earth-based sponsors should do everything possible to enhance their well-being and success in space, while learning from them about their experiences aloft.

2. Orientation

The second component in a space deployment system is a combination of self-instruction and training to prepare personnel for life beyond this planet. Oberg (1985) has described the astronauts' training, which offers a basis in this regard. However, with a more diverse population going into space, more generalized training would be needed. The curriculum would depend on the orbit, length of stay, and mission. Some of the training would be designed to develop skills in one's area of expertise, such as space technology or administration. Some of it might be to develop a secondary role to fulfill in the space community, such as food provider or paramedic. All would be expected to complete a basic course in space living that would deal with zero- and low-gravity compensation, life support systems, physical care and exercise, mental health services, and human relations. All would be given orientation to the cultural challenges of space communities and specific information about the cultures of their fellow crewmembers.

The learning program would include human behavior issues like communication, motivation, team-building and synergy, leadership, conflict management and negotiation, and family relations, both with those in space and with those left behind on Earth. Presumably there would be a need for all to learn something about space safety, the robotic and computer systems to be used at the space station or base, and the basic equipment that everybody would be expected to operate, such as an airlock or a rover. Possibly courses in astronomy, space migration, and space community development and systems, as well as in space recreation and constructive use of leisure time, might be among the innovative learning opportunities.

Instruction might include video case studies, simulations, programmed or computerized learning, and questionnaires. The content would draw heavily on information gathered about life in space by both American and Soviet space scientists. Instructors presenting live or media training should include those with experience in space.

There might be international, national, or regional space academies established by the turn of the century for such educational preparation. (The military academy model might be adapted for these new peace academies.) NASA, for example, might consider a location adjacent to the East-West Center near the University of Hawaii, where ample resources would be available. (Such a Pacific Basin site for an international space university was proposed in 1985 by Tetsuo Kondo, a member of the Japanese Diet, and by U.S. Senator Spark Matsunaga, and in 1986 by people addressing the National Commission on Space.) The faculty of a space academy should range from astrophysicists and astrochemists to behavioral scientists and astronauts. The program objectives would be to prepare spacefarers for effectiveness and excellence in their space cultural experience.

In addition to the example of the NASA training program for members of the U.S. astronaut corps, prototype space orientation programs can also be found in the educational offerings of the U.S. Space Camp and the International Space University founded in 1987.

3. Onsite Support and Monitoring

An effective space deployment system should include a third component of support services and monitoring by Earth-based sponsoring organizations. One dimension of this support would include all the food, supplies, equipment, facilities, communication, and transport necessary to maintain a community of humans in space. If we designate this as "physical support," the other dimension to be concerned with is "psychological support." That is, a program onsite at a space station or lunar base which will facilitate integration into the host environment and culture.

Upon arrival at the space location, the newcomer should benefit from an acculturation program, which may include being paired off with a seasoned "buddy," receiving indoctrination briefings, and being presented with media programs that will familiarize the person with the local scene, its dangers and its opportunities. Communication links have to be established so individuals can keep in touch with family and friends at home on Earth. New forms of video/audio recordings may be transmitted by satellite which will keep spacefarers informed of events in their families, hometowns, and organizations. To counteract alienation while boosting morale, Earth-based sponsors might have an information exchange with their representatives in space; it could range from organizational news bulletins to shopping services and training updates.

NASA today physically monitors the vital functions and well-being of its astronauts. Dr. James Grier Miller is planning a computer monitoring system for those on a space station. It is conceivable that organizational sponsors of space expatriates might wish to have a "space wellness program." This could be a more comprehensive approach that furthers the mental or holistic health of the space dwellers. It might include needs adjustment surveys, performance data analysis and reporting, and individual or group counseling. As individual and group data is amassed in an organization's computers, insights will be gained with which to improve the whole deployment system. Special attention should be paid to high-performing spacefarers (Harris 1988). Written records and videotapes of such top performers in space can be helpful in preparing others for the challenge of space living.

Such data will influence on-the-job training, design of space habitats and equipment, programming of recreational and other leisure time, work scheduling, procedures for making assignments and scheduling leave, and devising salary and benefit plans, especially for more hazardous service.

In the startup stages of a space operation, only emergencymedical assistance may be available to space dwellers. But, as the human space community grows and we move beyond frontier living conditions, more extensive physical and psychological assistance should be made available to spacefarers who need it. Problems may arise from the disruption of an individual's circadian rhythm, the effects of the gravity-free environment, the stress of lack of privacy, and the effects of lengthy space stays. There are many human factors related to space living that will have to be addressed by those responsible for deploying people in space, not the least of which is how to develop a viable sense of community with relevant psychological, social, political, and economic ideas.

A whole new infrastructure needs to be built on Earth to support space-based activities properly, including regional bases on this planet that are directly linked to a particular space enterprise. Similarly, an infrastructure has to be created at the space facility where humans will dwell, one that will deal with the needs and aspirations, weaknesses and failings of the species.

4. Reintegration

Until now human missions in space have been counted in minutes, days, weeks, and months. Present planning for the space station by NASA, for instance, calls for six to eight people working a 90-day shift. Current research indicates that humans can stay in space without unacceptable physical deterioration for up to 12 months before being rotated. Obviously, if human space migration is to take place, we must move beyond these constraints. Some have proposed that the first space settlers should be volunteers who commit to space either permanently or for a long time. They argue that the first colonists to the New World came to stay, not to be rotated back to Europe. Others point to the length of sheer travel time for interplanetary missions, such as 2-1/2 years to Mars and back, and discourage any plans for too-quick rotation of space colonists. Visionaries speculate that the human body will eventually adapt to the differences in space life, that a new gene pool and even a new breed may evolve over generations.

Starting with the construction crews and astronauts on the first

NASA space station, we can assume that guidelines will be set for safe lengths of stay. In the initial stages of space base development, we can expect regular reentry of space workers to the Earth's environment. If we are to avoid "reentry shock," the process of preparing people for that transition should begin on the high frontier. Perhaps astronauts who have been to the Moon and back would make the best consultants for designing such programs. Space people will have to readjust both physically and psychologically to the home planet. Their sponsoring organizations should have a plan for facilitating their reintegration into Earth's lifestyle and tempo. Reentry counseling may range from reassignment to occupational activities on this planet to preparations for return to the high frontier. Some will experience "you-can't-go-home-again" syndrome, while others will complain of a variety of traumas and crises upon their return and may even require outplacement from space services or assistance with a divorce. The interplanetary experience may prove to be more profound than cross-cultural experiences here on Earth.

To close the space deployment loop, we should gather and analyze information from returning expatriates. Data gathered through questionnaires, interviews, or group meetings should be computerized. This data should be analyzed to improve the future recruitment, selection, and training of spacefarers and to improve the quality of life in space communities.

San Diego State University professor Arthur Ellis has begun to examine the role of social work in the space age.* As large space colonies are planned, he believes that the human services field can contribute to establishing policies, services, and ethics that will protect and enhance society's human resources in space. Ellis envisions the application of social work methodology to the stress and depression experienced when individuals are separated from their families by space missions or when they must endure long periods together in a space community. The hazards of being human in an alien environment may demand that some form of space psychotherapy be available both on the high frontier and on return to Spaceship Earth.

Conclusion

The human race is in transition from an Earth-based to a space-based culture, and the process of this "passover" may take centuries.

*Personal communication

We *Homo sapiens* are by nature wanderers, the inheritors of an exploring and colonizing bent that is deep . . . in our evolutionary past. . . . Whereas technology gives us the capacity to leave Earth, it is the explorer's bent, embedded deep in our biocultural nature, that is leading us to the stars.

(Finney and Jones 1985)

Anthropologist Finney and astrophysicist Jones remind us that it is the species called "wise"—*Homo sapiens*—which evolved biologically and adapted culturally so as to populate and make a home of this planet. These same inclinations and capacities propel humanity into the solar system and may be the catalyst for interstellar migrations. Finney and Jones speculate on an explosive speciation of intelligent life as far as technology, or the limits placed by any competing life forms originating elsewhere, will allow.

The humanization of space, in any event, implies the extension of Earth cultures, both national and organizational, into the universe. It means creating not just new space technologies, methods of transportation, and habitats but a wholly new lifestyle and way of thinking that evolves appropriate societal and economic structures, legal and political systems, art and recreation, as well as suitable life support. Early in the next century our extraterrestrial pioneers may produce the first space-born generation that is not psychologically dependent upon Earth. In time, these high frontier dwellers may raise a different type of human.

The "creeping" begins with the Shuttle that takes us 300 miles or so to a space station, a platform for assembling the world's best scientists and engineers in low Earth orbit. The "walking" begins when we can regularly, economically, and safely extend our presence 23 000 miles above the Earth's surface to geosynchronous Earth orbit. There or at bases on the Moon and Mars we will mature and step into the universe and a new state of being.

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Future Space Development Scenarios: Environmental Considerations

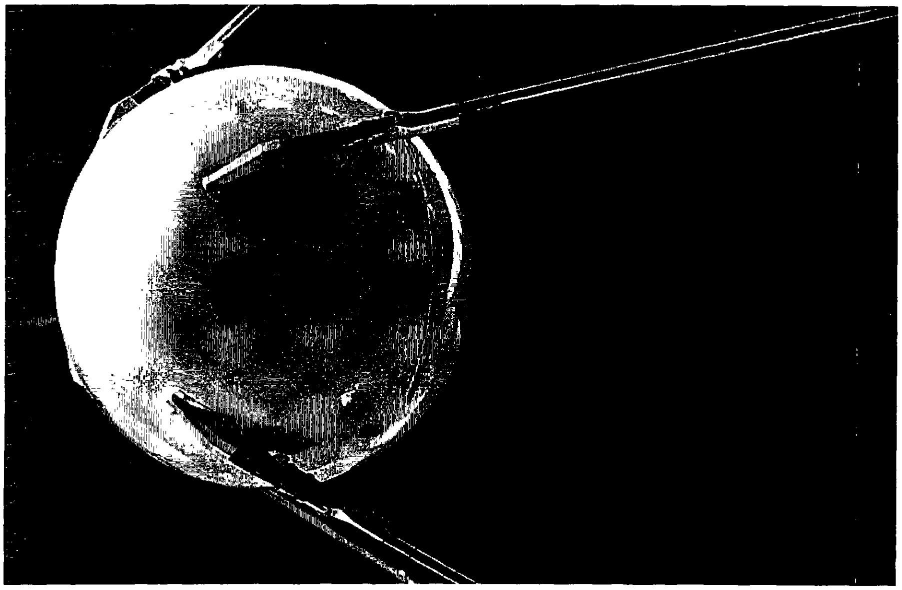
Richard Tangum

Introduction

Human presence in space has expanded dramatically since the first Sputnik of October 1957. Between 1959 and 1976, 40 spacecraft were launched into lunar orbit or to the surface of the Moon.

Spaceflights That Provided Lunar Data

Apollo missions	(1968-1972)	9	manned flights
Luna series	(1959-1976)	13	Russian probes
Surveyor	(1966-1968)	5	unmanned landings
Ranger	(1964-1965)	3	preimpact photography flights
Zond	(1965-1970)	4	unmanned flybys
Lunar Orbiter	(1966-1967)	5	orbital photography flights
Explorer 35	(1967)	1	orbital flight



Sputnik I

The "beep beep" of Sputnik I in October of 1957 changed the world's perception of itself. This full-scale model of the basketball-size satellite was on display at the Soviet Pavilion at the Paris Air Show.

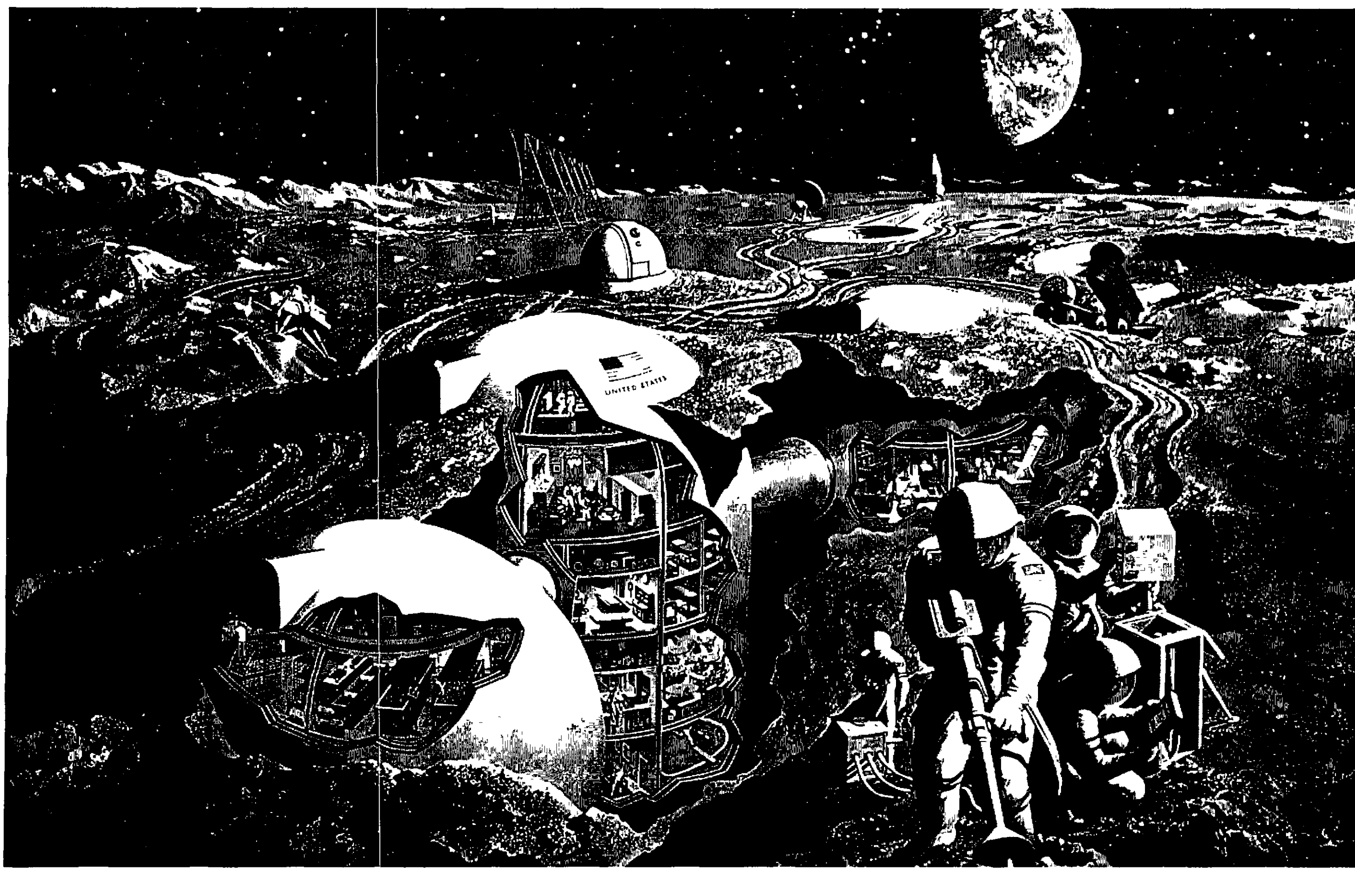
Likewise, the launching of satellites into low Earth orbit (LEO) and geosynchronous Earth orbit (GEO) has continued unabated. This presence in space—to include the lunar surface, asteroids, and Mars—will increase dramatically in scale and scope within the next quarter century. NASA's plans for a space station in LEO are already under way.

The National Commission on Space appointed by President Reagan calls for human outposts on the Moon by 2005 and on Mars by 2115. The Commission believes that an aggressive plan should be adopted

> To lead the exploration and development of the space frontier, advancing science, technology, and enterprise, and building institutions and systems that make accessible vast new resources and support human settlements beyond Earth orbit, from the highlands of the Moon to the plains of Mars.

The Commission further states that a major thrust should be exploring, prospecting, and settling the solar system. Furthermore, space enterprises should be encouraged to benefit people on Earth. President George Bush, in his speech at the Air and Space Museum on the 20th anniversary of the Apollo 11 landing, both echoed an Apollo 11 astronaut and reinforced the Commission's goals by stating

> Mike Collins said it best: "The Moon is not a destination; it's a direction." And space is the inescapable challenge to all the advanced nations of the Earth. And there's little question that, in the 21st century, humans will again leave their home planet for voyages of discovery and exploration. What was once improbable is now inevitable. The time has come to look beyond brief encounters. We must commit ourselves anew to a sustained program of manned exploration of the solar system, and, yes, the permanent settlement of space. We must commit ourselves to a future where Americans and citizens of all nations will live and work in space.



Lunar Colony, as Conceived in February 1969

This painting and its caption, published 5 months before the Eagle *of Apollo 11 touched down on the Moon and brought back the first lunar samples, is remarkable not for its mistakes in detail, which analysis by hundreds of scientists of the nearly 400 kilograms (841 pounds) of lunar rocks collected by the Apollo astronauts has subsequently revealed, but rather for the accuracy of its general idea of facilities and activities that now, "a generation" later, we are planning to build and carry out on the Moon:*

"Frontiersmen of the Space Age, engineers and technicians colonize the moon. Drawing on the most advanced thinking of experts, artist Davis Meltzer portrays a lunar outpost that might be possible in a generation. A survey team drills core samples and maps the surface as an attendant monitors the oxygen supply. Aluminum habitation modules lie almost buried for protection against micrometeorites and temperatures that fluctuate 500°F. between noon and night. In a laboratory module, foreground, biologists observe animals and experiment with raising vegetables in fertilized water. A multi-level main module encloses dressing rooms for entering and leaving, medical dispensary, dormitory, kitchen, and dining and recreation areas. Pressurized tunnel leads to a smelter, where lunar rock quarried on the surface is processed for the water chemically locked within it. The water not only fills the station's swimming pool, but also yields oxygen for breathing and hydrogen for fuel for a flying vehicle, far left. A fencelike radio telescope probes deep space, and an optical scope in a small observatory studies the heavens, undimmed by earth's atmosphere. Beside a hangar pit, a commuter rocket poises for return to the blue planet earth."

Artist: Davis Meltzer

Illustration and caption taken from Kenneth F. Weaver, 1969, "The Moon, Man's First Goal in Space," National Geographic ***135*** *(2—Feb.): 206-230*
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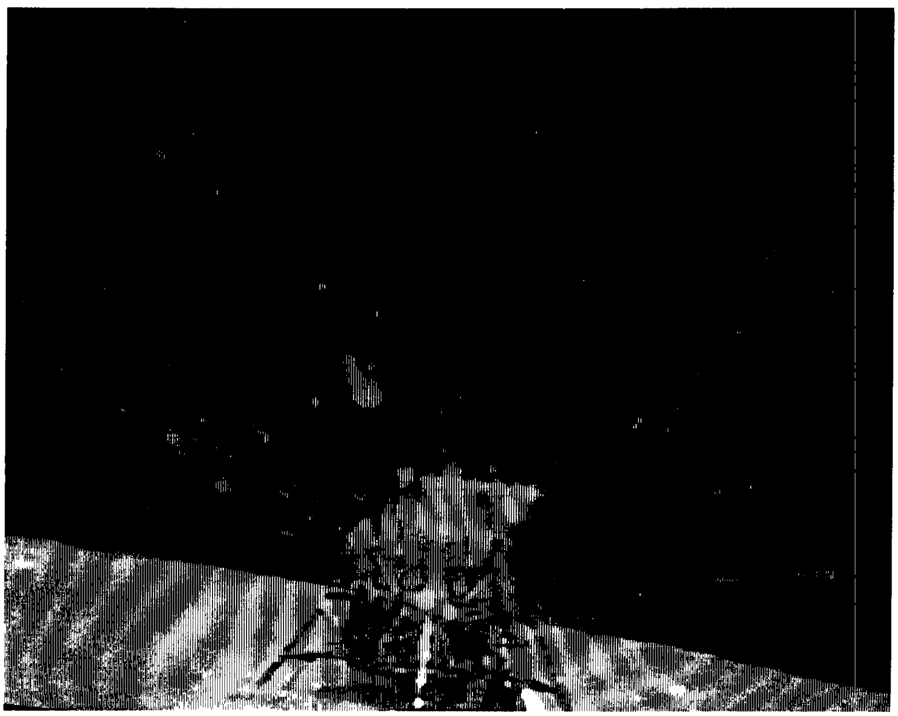


Apollo 16 Lift-Off From the Moon

The confetti-colored sparkles of the lunar module lift-off for each of the last three Apollo missions were seen by millions of people, thanks to a TV camera mounted on the lunar rover. We were glad to see our astronauts lifted safely from that far-off surface to join their fellows in the orbiting command and service modules and come home to Earth. But, as we contemplate going back to the Moon, to establish a permanent base, we must be concerned about the effect that our built environment will have on the natural environment there.

Studies of the potential use of nonterrestrial materials could have far-reaching implications for the environments of low Earth orbit and the lunar surface, in terms of both use and the prevention of possible contamination. A need is clearly emerging for some form of environmental assessment and management to determine what to use space or planetary surfaces for and how to do it; what changes to tolerate and what standards to impose; and how to meet these standards.

The term *environment* in space can be used in three different senses: first, the natural environment of soils, gases, and organisms that may be present; second, the built environment, including manned satellites and the areas humans build to live and work in; third, the social environment—culture, law, and economics. Of immediate concern is the effect of the built environment on the natural environment in space.

Potential Research

Many of the initial activities potentially associated with the establishment of a lunar base will involve research. A lunar base setting with low gravity and a vacuum environment makes it possible to conduct unique experiments that are not possible on Earth. These factors, plus added seismic stability, make the Moon a perfect observatory platform. The far side of the Moon is especially suited for radio astronomy because its pristine environment, shielded from radio frequencies, allows measurements over a wide range of wavelengths (see fig. 15). Solar wind studies are easier on the Moon because of the lack of an atmosphere and also the lack of a large magnetic field. Furthermore, the Moon acts as an absorbing surface to the charged solar plasma. Geological studies can answer questions about the Moon's history, its evolution, structure, composition, and state. Practical resource development questions will arise about where large quantities of various ores can be found and how to mine them economically.

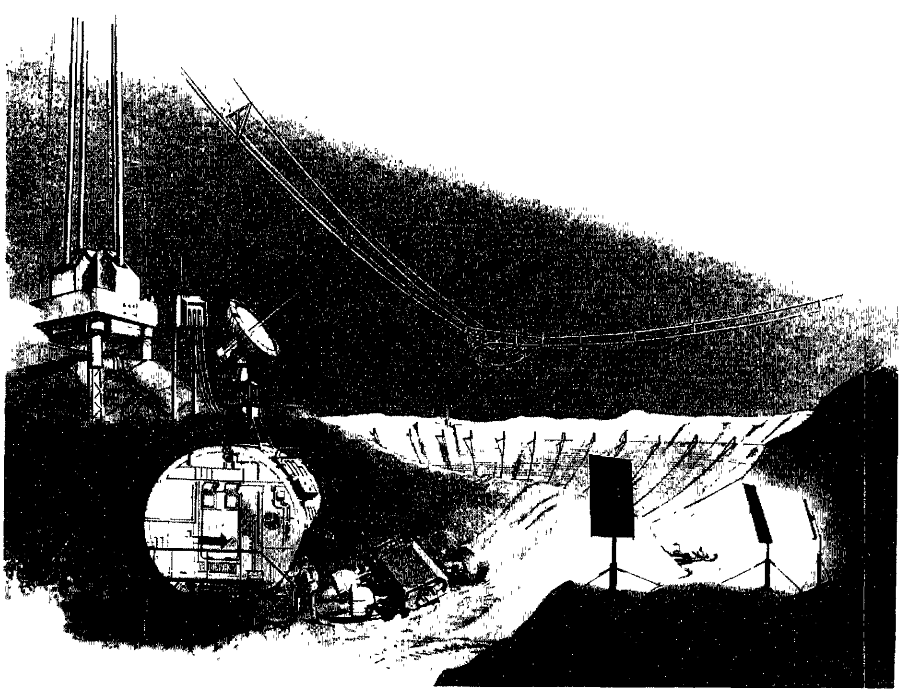


Figure 15

Radio Telescope on the Far Side of the Moon

In this artist's concept, a radio telescope has been placed in a meteorite crater on the far side of the Moon. The parabolic grid in the crater reflects the signal to the steerable collector suspended by cables. The lunar far side may prove to be an ideal location for radio telescopes because nearly all radio frequency noise generated by human activity on Earth will be blocked out by the Moon itself. In the concept shown here, the radio telescope is human-tended but is operated by remote control most of the time. Information from the telescope is beamed to a lunar communications satellite which relays the data back to Earth. Other radio telescope designs have also been proposed, including large-area phased arrays which do not require parabolic reflectors. While early lunar base installations will likely be on the near side of the Moon, far side sites for radio telescopes will likely follow because of the clear advantage of such a location.

An Illustration of the Problem

Mining of the lunar surface is an area of potential environmental concern. This issue was voiced by the Lunar Base Working Group, meeting at Los Alamos National Laboratory in 1984:

> Most lunar scientific activities require that the unique lunar environment be preserved. Lunar base operations might affect this environment in *adverse* ways, especially if industrial operations expand.

Specific potential environmental impacts were cited: increased atmospheric pressure, which could change atmospheric composition and compromise astronomical observations, and increased very low radio frequency background through satellite communication networks, which could affect the use of the far side of the Moon for radio telescopes.

Unprotected by any atmosphere, the Moon will accumulate scars of impacts by humans at an increasing rate. In contrast, the Earth will exhibit a more youthful appearance, since it is constantly rejuvenated by geological processes such as erosion by wind and water. On the Moon, micrometeoritic action turns over the top 3 mm of the lunar surface every 1 000 000 years (Gault et al. 1975). In this time span, the lunar surface is destroyed, recreated, and shaped.

Extensive mining efforts on the Moon, however, could scar its surface irreversibly. Numerous components of mining on the Moon must be environmentally assessed: the scale of the mining operation, its associated development, and its technological features. Factors affecting the scale of mining include

- Ore quality
- Size of ore body
- Availability of energy
- Cost of operation
- Type of operation

Strip mining would probably be the most efficient method for producing ore (see fig. 16). There could remain the desolation of steep piles of discarded regolith, alternating with the trenches from which the regolith is removed. The Moon, in time, could become a visual and scientific wasteland. Laws requiring backfilling of the trenches and recontouring of the ground surface to some semblance of its original state would be needed.

Development and technological features affecting the environmental impact include

- Size of mining installation (land required)
- Volume of spoil generated
- Nature of energy source used
- Nature of transportation system used
- Nature and volume of pollution released
- Use of explosives
- Drilling processes

Oxidic minerals will probably be the first resource mined on the Moon for life support and rocket propellant. Although projected ore volume for initial production of oxygen would be low (82 cubic meters of unconcentrated fines per day), eventual development of larger settlements would require a vast mining operation to sustain them. Approximately 100 000 tons of regolith (10-percent usable ilmenite content) are needed to produce 1000 tons of oxygen in a carbothermal oxygen production plant (Cutler and Krag 1985). This translates into a mining operation that extracts 50 000 cubic meters of regolith for each 1000 tons of oxygen produced.

Selenopolis, a fully developed lunar settlement envisioned by Krafft Ehricke (1985), could require vast quantities of oxygen per year for its inhabitants' use for life support and rocket propellant. Annually to produce 500 000 tons of oxygen, an area 7.07 kilometers square and 5 meters deep would have to be mined.

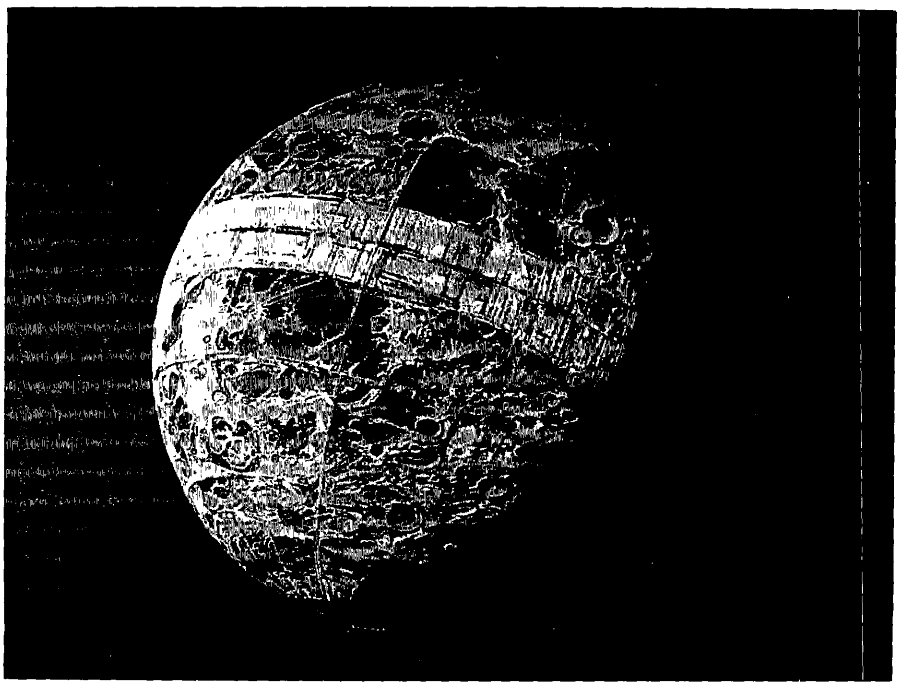
Figure 16

Three-Drum Slusher

This lunar mining system is called a "three-drum slusher." It is similar to a simple two-drum dragline, in which a bucket is pulled by cables to scrape up surface material and dump it into a waiting truck. The third drum allows the bucket to be moved from side to side to enlarge the mining pit. Surface mining of unconsolidated lunar regolith, using versions of draglines or front-end loaders, will probably be done at a lunar base initially, although deeper "bedrock" mining is also a possibility and underground mining may even be attractive if appropriate resources are located.

Although the Moon does not have an atmosphere as such, it does have an exosphere in which individual particles are captured by its gravitational field. Each one of the Apollo missions between 1969 and 1972 added more than 10 tons of exhaust gases to the exosphere. Over the 3-year period, more than 60 tons of gases were released on the lunar surface. And the five Luna missions that returned samples from the Moon between 1970 and 1976 probably added a similar amount. Although subsequent measurements failed to detect their presence, these gases had a sufficiently high molecular weight that their dispersal from the gravitational field of the Moon would occur only through a very slow process. What happened to these gases? A likely answer suggested by Zdenek Kopal (1979) is that the gases were rapidly absorbed by the lunar crust and bound in a solid state. The implications of the release of large quantities of gases of different types is unknown.

We must remember that the Moon, in its pristine condition, serves as an important, well-preserved fossil of the solar system. Much remains to be discovered about the evolution of the Earth and the solar system. Very little geological evidence has



"Moon, 2000"

Would-be developers may find this image of the Moon overly optimistic, at least by the year 2000. But environmentalists like Rick Tangum may view the image, by visual futurist Syd Mead, more pessimistically. Tangum is concerned about the scale of a mining operation necessary to support a large lunar settlement. Unmanaged development of the Moon could destroy its potential to reveal scientific information about the early history of the solar system.

Artist: Syd Mead

been discovered about the first billion years of Earth's 4-1/2 billion year history. Geological discoveries on the Moon will continue to clarify Moon-Earth and solar system history (see box). Unmanaged development of the Moon could destroy this potential.

What We've Learned About the Earth by Studying the Moon

- The Earth formed during the same planetary accretionary period as did the Moon—about 4.5 billion years ago. Much older rocks are found on the dry, airless, rapidly cooled Moon, whose crust has not been eroded and subducted like the Earth's has.
- The Earth, like the Moon, continued to be bombarded by planetesimals from its formation down to about 3.9 billion years ago. This record, too, is preserved on the relatively inactive Moon.
- The most likely story of the origin of the Moon explains why the Moon is less dense than the Earth: A planetesimal the size of Mars collided with the Earth and splashed some of the Earth's mantle, along with the silicate mantle of the impactor, into orbit around the Earth, where the debris accreted to form the Moon. The metallic core of the impactor, on the other hand, accreted to the Earth. This collision tilted the Earth 23° from the plane of the ecliptic and gave it its spin.
- The Earth was once completely molten, allowing its differentiation, the heavier elements sinking toward its still molten core, the lighter elements rising to eventually form its granitic continental crust. Traces of such chemical separations, occurring while the Moon was covered by a "magma ocean," are still preserved in its rocks.
- Even after the period of heaviest bombardment (4.5 to 3.8 billion years ago), impacts by asteroids, meteorites, and comets have continued to be significant, albeit random, events in geological history, though the evidence has been mostly erased on Earth. One such catastrophic impact has been found to be coincident with the extinction of the dinosaurs.
- The eruption of basalts, derived by the partial melting of the mantle, has been common on the solid planets and their satellites and on some asteroids. This igneous process is seen in the dark lava flows that filled the lunar basins we call "maria" (or "seas"), more of them on the near than on the far side of the Moon.

And an unanswered question:

> Why does the Moon lack a magnetic field while the Earth has a relatively strong one? Is it because the Moon has only a small, if any metal core? If so, then why is a "fossil" magnetism preserved in lunar rocks?

Compiled from information provided by Michael B Duke, S. Ross Taylor, John A. Wood, and the Solar System Exploration Division at NASA Headquarters.

Conclusion

The formation of positive attitudes and values concerning the environment of space, as the basis for assuming a wise stewardship role, is becoming increasingly important as many nations begin their journeys into space. A strong emphasis should be placed on fostering an international space environmental ethics.

The object of environmental assessment and management in space should be to define what interplanetary regulatory procedures are needed to avoid unnecessary environmental damage and to monitor the effectiveness of such avoidance. The first requirement for research is to narrow the field of concern to areas where there could be an increased scale of development in space in the immediate future. Research needs to be focused on methodologies for defining the environmental systems involved (e.g., the lunar surface) and then recognizing key variables in the system that are fragile and need to be respected. Criteria for environmental quality should emerge which identify, in the case of the lunar surface, how much mining activity can be safely undertaken and what quantity of exhaust gases can be released over a given period of time. Only then will humans be most able to evaluate the likely consequences of ventures into space and be able to best preserve the newest frontier for posterity.

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Applications of Living Systems Theory to Life in Space*

James Grier Miller

Introduction

Earth, so far as we know, is the only planet in our solar system on which living systems have ever existed. Since Earth's primeval atmosphere lacked free oxygen and therefore had no ozone layer to protect primitive cells and organisms from the Sun's killing radiation, life evolved in the sea for the first two billion years. The biological activity of primitive algae is considered a major factor in creating our oxygen atmosphere, making it possible to colonize land.

Now the human species is contemplating a second great migration, this time into space. Human settlements, first on space stations in orbit and then on bases on the Moon, Mars, and other planetary bodies, are in the planning stage.

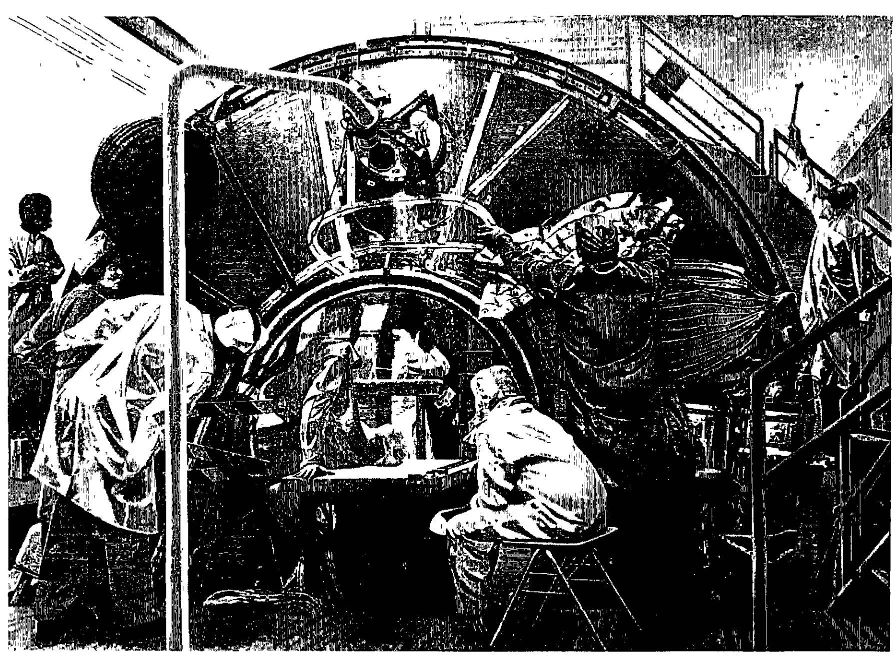
Planning for nonterrestrial living requires a reorientation of the long-range strategic purposes and short-range tactical goals and objectives of contemporary space programs. The primary focus must be on the human beings who are to inhabit the projected settlements. This implies a shift in thinking by space scientists and administrators so that a satisfactory quality of human life becomes as important as safety during space travel and residence. Planners are challenged not only to provide transportation, energy, food, and habitats but also to develop social and ecological systems that enhance human life.

Making people the dominant consideration does not diminish the need to attend to technologies for taking spacefarers to their new homes and providing an infrastructure to sustain and support them in what will almost certainly be a harsh and stressful setting (Connors, Harrison, and Akins 1985).

As clear a vision as possible of human organizations and settlements in space and on nonterrestrial bodies in the 21st century should be gained now. A beginning was made by the National Commission on Space (1986) in depicting the human future on the space frontier. Behavioral scientists, particularly those with a general systems orientation, can contribute uniquely to this process. They can do research to improve strategic and programmatic planning focused on human needs and behavior. The results should prove to be the drivers of the mechanical, physical, and biological engineering required to create the space infrastructure.

*Presented at the NASA-NSF conference The Human Experience in Antarctica: Applications to Life in Space, held in Sunnyvale, CA, August 17, 1987.

When we envision nonterrestrial stays of long duration, we must plan for quite different social phenomena than we have seen in space missions up to now. Astronauts have lived on space stations for periods of a few weeks or months at most. The great majority of missions have been relatively brief. Such missions have required the daring and initiative of carefully selected and highly trained astronauts equipped to accomplish limited goals. If people are to remain permanently in settlements far from Earth, however, they cannot endure the inconvenient, uncomfortable, and difficult working and living conditions that have been the lot of the highly trained and motivated professionals who have gone into space over the past 30 years. Months and years in a space environment are an entirely different matter. Motivation diminishes over time and long-continued discomforts are hard to bear.



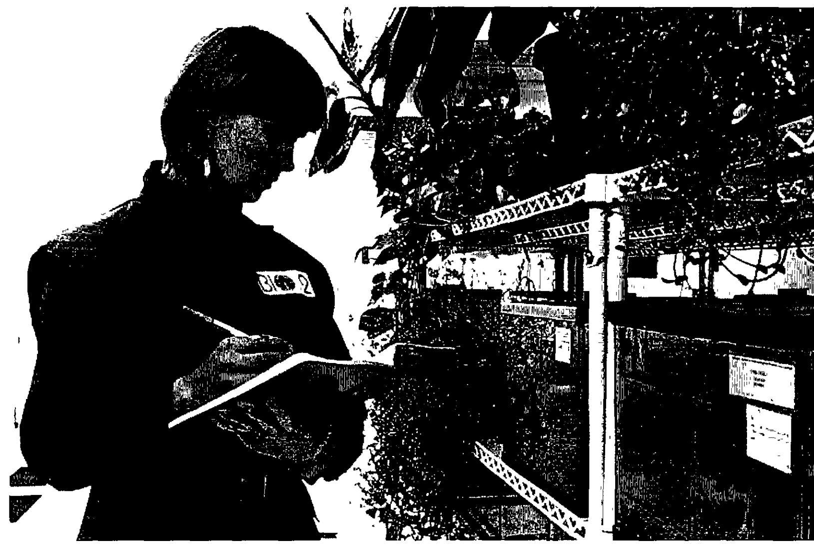
Spacelab 1

As technicians examine the Spacelab module, a physician examines a prospective occupant. As we contemplate long journeys to other planets and lengthy stays in space, we must plan not only for the safe transportation and life support of spacefarers but also for their comfort and well-being. The high motivation that has characterized astronauts and cosmonauts in space flights so far cannot be expected to endure avoidable difficulties throughout long missions.

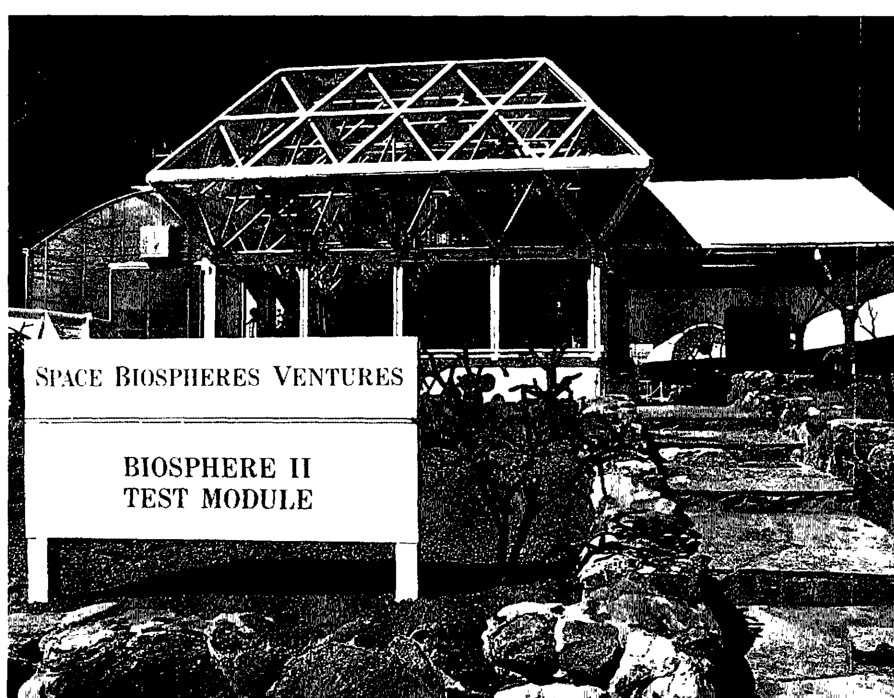
Artist: Charles Schmidt (NASA Art Program Collection)

If men, women, and perhaps even children live together in nonterrestrial locations which, even with excellent communications to Earth, are inevitably isolating, their behavior will undoubtedly be different from any that has so far been observed in space. A new space culture may well arise (see Harris's paper on space culture in this volume). This is particularly likely in an international program that includes people from different nations and diverse cultures. It is not too early to begin systematically to try to understand what such settlements will be like in order to plan wisely for them.

No place on Earth closely resembles the conditions in space, on the Moon, or on other planetary bodies. The harsh environmental stresses and the isolation that must be faced by people who winter over in Antarctica, however, are similar in many ways. If the logistical problems of doing research there and the attendant costs can be coped with, perhaps Antarctica is the best place within the Earth's gravity field to analyze the problems of life in space and even to put a space station simulator or to model a lunar outpost. Also it is a good place to develop plans for continuous monitoring of human behavior under rigorous conditions, by procedures such as those based on living systems theory, which is outlined below. If that kind of Antarctic research is infeasible or unduly costly, we can consider doing space station research at other locations, such as the Space Biospheres at Oracle, Arizona, or on space station simulators at Marshall Space Flight Center in Huntsville, Alabama; at McDonnell Douglas Corporation in Huntington Beach, California; or at Ames Research Center at Moffett Field, California.



Researcher notes condition of insect-growing area at Biosphere II



Biosphere II Test Module

On November 2, 1989, botanist Linda Leigh stepped inside an airlock and entered an ecosystem separate from the biosphere of the Earth. For the next 21 days, the air she breathed, the water she drank, and the food she ate were generated by the ecosystem within the 17 000-cubic-foot airtight glass and steel Test Module of Space Biospheres Ventures in Oracle, Arizona. Leigh harvested fruits, vegetables, herbs, and fish grown in the module and prepared them in the module's human habitat section, which includes an efficiency kitchen, a bathroom with a shower, a bed, and a study area with a desk. She communicated with colleagues and observed air and water quality data, by computer monitor In this, as in the previous two tests, all environmental quality indicators remained well within safety limits and the human inhabitant remained in excellent health and spirits. James Grier Miller suggests the application of measures based on living systems theory to human behavior in such a simulation of life on a space station

Space Station Trainer

This accurate physical mockup of a space station module is used to train prospective crewmembers in the use of equipment. The Johnson Space Center also has simulators, which, although they do not look from the outside as the actual hardware will look, do give crewmembers the feeling of being in space. It is not possible to make a trainer/simulator that both looks and feels like the real thing. NASA planners also look at analog situations, like the isolated environment at the South Pole, to study how people function under such rigorous conditions.

Synopsis of Living Systems Theory

Living systems theory (LST) provides one possible basis for such research. This is an integrated conceptual approach to the study of biological and social living systems, the technologies associated with them, and the ecological systems of which they are all parts. It offers a method of analyzing systems—living systems process analysis—which has been used in basic and applied research on a variety of different kinds of systems.

Since 1984 my colleagues and I have been examining how LST can contribute to the effectiveness of space planning and management. At the NASA summer study in LaJolla, we focused on strategic planning for a lunar base. Since then a team of behavioral and other scientists has explored ways in which a living systems analysis could be employed by NASA to enhance the livability of the Space Shuttle and eventually of the space station.

The LST approach to research and theoretical writing differs significantly from that commonly followed in empirical science. One reason for this difference is that LST was developed by an interdisciplinary group of scientists rather than representatives of one discipline. Many members of the group were senior professors with national and international recognition in their own specialties. All members had advanced training in at least one discipline. But they agreed on the importance of achieving unity in science, working toward the goal of its ultimate integration by developing general theories. Research concerned with living systems is designed with this goal in mind. It focuses on the following concerns.

1. Compartmentalization of Science

Modern science suffers from structural problems that have their roots in conceptual issues. The organization of universities by departments, and the structure of science generally, emphasizes the separate disciplines. The rewards of academic life are given for becoming expert in a specialty or subspecialty. It is important, however, that, although the major work of science must be done by specialists, they should all realize that they are contributing to a mosaic and that their work fits, like a piece of a jigsaw puzzle, into an overall picture.

In the real world of daily affairs, whether one is dealing with computers and information processing or with housing, finance, legislation, or industrial production, the problems are always interdisciplinary. The problems that face space enterprises are also interdisciplinary. Each major project needs the skills of engineers, lawyers, economists, computer scientists, biologists, and social scientists in different combinations.

2. Inductive General Theory

There are two major stages in the scientific process: first, the inductive stage, and, second, the deductive stage. The inductive stage is logically prior. Scientists begin the first stage by observing some class of phenomena and identifying certain similarities among these phenomena. Then they consider alternative explanations for these similarities and generate hypotheses to determine which explanation is correct.

A goal of science that has been recognized for centuries is the development of both special theories of limited scope and general theories that unify or integrate special theories and cover broader spheres of knowledge. It is usually necessary to start with special theories that deal with a limited set of phenomena. Middle-range theories concerned with a greater number of phenomena come later. Ultimately a body of research based on these leads to general theories that include a major segment of the total subject matter of a field or of several fields.

The desirability and usefulness of general theory is more widely acknowledged in some disciplines, like mathematics and physics, than in others. Unfortunately many students of science and even senior scientists have not been taught about this goal and are unaware of it. Of course scientists, under the principles of the First Amendment and of academic freedom, may generate their hypotheses any way they please. Then they can test or evaluate them by collecting data and either confirm or disprove them. The findings resulting from such a procedure, however, may not have any discoverable relationship to the findings of any other research in the same field.

Voluntary scientific self-discipline in the mature sciences leads researchers to prefer to carry out studies which test hypotheses that distinguish critically between alternative special theories, middle-range theories, and ultimately general theories. The goal of research on LST is to collect data to make deductive tests of hypotheses derived from inductive, integrative theory.

3. Common Dimensions

If scientists or engineers from different fields are to work together, it is desirable that the dimensions and measurements they use be compatible. Experimenters in physical and biological sciences ordinarily make their measurements using dimensions identical to those used by other scientists in those fields, or other units that have known transformations to them.

It should eventually be possible to write transformation equations to reduce dimensions of any of the disciplines of physical, biological, or social science into common dimensions that are compatible with the meter-kilogram-second system of measurement so that specialists in different fields can communicate precisely. Investigators studying LST attempt to use such dimensions whenever it is possible.

If some phenomena of living systems cannot be measured along such dimensions, one or more others may have to be used. If this is done, however, an explicit statement should always be made that those particular dimensions are incommensurable with the established dimensions of natural science. Furthermore, resolute efforts should be made to discover transformation equations that relate them to the established dimensions. Our experience indicates that in many cases this can be done. The use of transformation equations is advocated rather than an attempt to go directly to some system of common dimensions because people in different disciplines often feel that the measures to which they are accustomed are preferable in their own fields. Transformation equations are a reasonable first step to common dimensions.

Comparable dimensions for living and nonliving systems are increasingly useful as matter-energy and information processing technologies become more sophisticated and are more widely employed throughout the world. The design of person/machine interfaces, for example, is more precise and efficient when both sides are measured comparably. Engineers and behavioral scientists are able to cooperate in joint projects much more effectively than they ordinarily have in the past. Such cooperation greatly facilitates space science. Such comparability of dimensions is a main theme of the program projected in this proposal.

4. Coexistence of Structure and Process

It is important not to separate functional (that is, process) science from structural science. Psychology and physiology are process sciences at the level of the organism, and sociology and political science are process sciences at the level of the society. Gross anatomy and neuroanatomy are structural sciences at the level of the organism, and physical geography is a structural science at the level of the society.

A psychologist or neurophysiologist, however, is inevitably limited if she or he cannot identify the anatomical structure that mediates an observed process, and an anatomist can have only a partial understanding of a structure without comprehending its function. Consequently, whenever a process has been identified but the structure that carries it out is not known, it should be an insistent goal of science to identify the structure. The opposite is also true: It should be an insistent goal of science to identify the process or processes that a structure carries out. Often this is disregarded because it is not thought to be urgent. The main reason for this appears to be that, in the academic world, process or functional sciences are administratively separate from, and in poor communication with, their relevant structural sciences (e.g., gross anatomy at the level of the organism or physical geography at the level of the society).

5. Biosocial Evolution

Living systems are open systems that take from the environment substances of lower entropy and higher information content (food, energy, information) than they put back into the environment (waste, heat, noise). This thermodynamically improbable increase of internal information (negative entropy), which does not occur in nonliving systems, makes it possible for them to grow, do work, make products, and carry on other life functions.

On the basis of a mass of supporting scientific evidence, LST asserts that over the last approximately 3.8 billion years a continuous biosocial evolution has occurred, in the overall direction of increased complexity. It has so far resulted in eight *levels* of living systems: cells, organs, organisms, groups, organizations, communities, societies, and supranational systems. This evolution came about by a process of *fray-out* (see fig. 1) in which the larger, higher-level systems evolved with more (and more complex) components in each subsystem than those below them in the hierarchy of living systems. Fray-out can be likened to the unraveling of a ship's cable. The cable is a single unit but it can separate into the several ropes that compose it. These can unravel further into finer strands, strings, and threads.

Systems at each succeeding level are composed principally of systems at the level below. Cells have nonliving molecular components, organs are composed of cells, organisms of organs, groups are composed of organisms, and so on. Systems at higher levels are *suprasystems* of their component, lower-level systems, which are organized into *subsystems*, each of which performs one of the activities essential to all living systems.

Our identification of these subsystems was under way by 1955. By 1965 we had identified 19 of them. A 20th, the timer, was identified only recently (Miller 1990). It is interesting that a group of researchers at Lockheed Corporation in 1985, apparently without any underlying conceptual theory or any knowledge of our previous work, identified a set of elements and subelements of the living and nonliving aspects of a space station with significant similarities to our subsystems. They were not wholly comparable, however. One incompatibility is that the Lockheed researchers listed as elements or subelements not only what we call "subsystems" but also what we call "levels" and "flows."

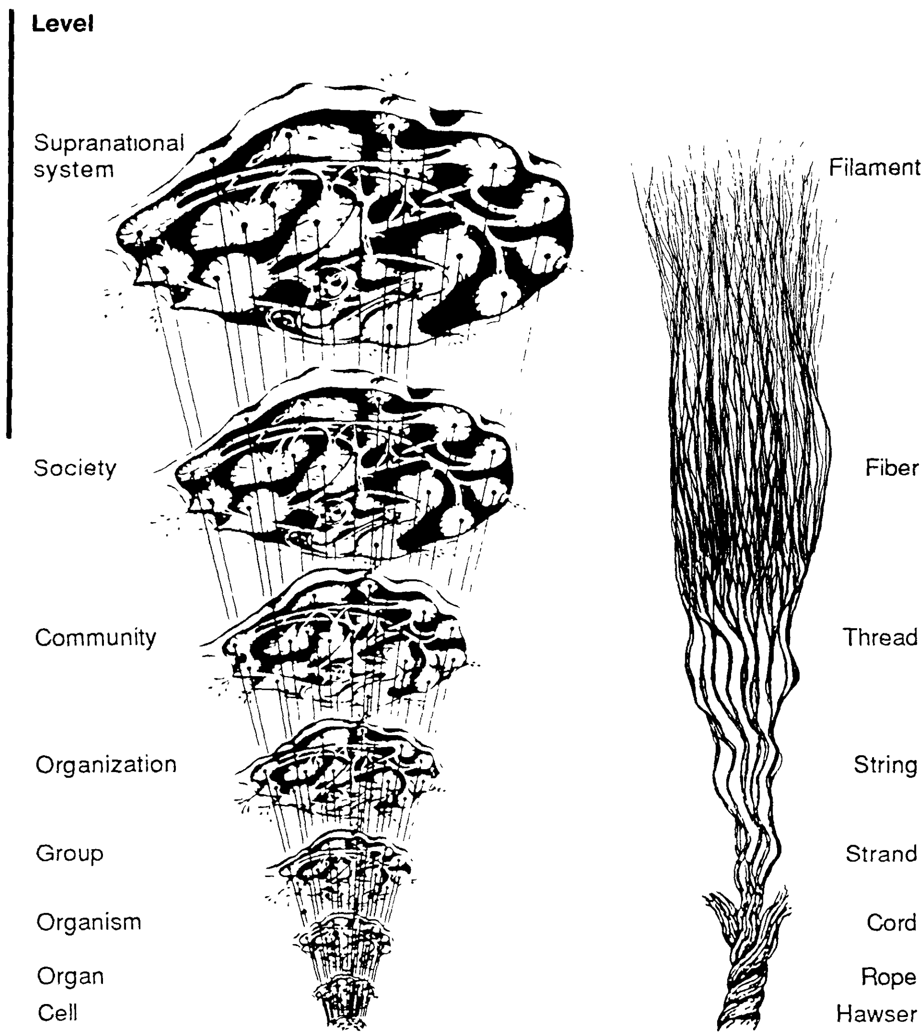


Figure 1

Fray-Out

We can visualize the relationship among the levels of living systems by comparing a cell to a ship's cable. As the more complex levels "fray-out" from their cellular form, they grow and thus produce the larger forms. Each of these levels, small or large, is composed of the same 20 subsystems, however.

6. Emergents

The fact that systems at each level have systems at the level next below as their principal components doesn't mean that it is possible to understand any system as just an accumulation of lower-level systems. A cell cannot be described by summing the chemical properties of the molecules that compose it, nor can an organism be described by even a detailed account of the structure and processes of its organs. LST gives no support to reductionism. At each higher level of living systems there are important similarities to the lower levels, but there are also differences. Higher-level systems have emergent structures and processes that are not present at lower levels. Emergents are novel processes, made possible because higher-level systems have a greater number of components with more complicated relationships among them. It is this increased complexity that makes the whole system greater than the simple sum of its parts, and gives it more capability. Higher-level systems are larger, on average, and more complex than those below them in the hierarchy of living systems. They can adapt to a greater range of environmental variation, withstand more stress, and exploit environments not available to less complex systems.

7. The Subsystems of Living Systems

Because of the evolutionary relationship among them, all living systems have similar requirements for matter and energy, without which they cannot survive. They must secure food, fuel, or raw materials. They must process their inputs in various ways to maintain their structure, reproduce, make products, and carry out other essential activities. The metabolism of matter and energy is the energetics of living systems.

Input, processing, and output of information is also essential in living systems. This is the "metabolism" of information.

LST identifies 20 essential processes which, together with one or more components, constitute the 20 subsystems of living systems (see table 1). With the exception of the 2 subsystems of the learning process, which seem to have evolved with animal organisms, all 20 processes appear to be present at each of the eight levels, although they may not be present in all types of systems at a given level. Bacteria, which are cells, for example, have no motor subsystems but many other types of cells have motor components and can move about in the environment or move parts of the environment with relation to them. Similarly, some groups and organizations process little or no matter-energy. Some systems clearly have components for certain processes but these components have not been identified. This is largely true for organism associating. Even the simplest animals have some form of learning but the components are not certainly known.

TABLE 1. *The Subsystems of Living Systems*

	Subsystems which process both matter-energy and information
1	*Reproducer,* the subsystem which carries out the instructions in the genetic information or charter of a system and mobilizes matter, energy, and information to produce one or more similar systems
2	*Boundary,* the subsystem at the perimeter of a system that holds together the components which make up the system, protects them from environmental stresses, and excludes or permits entry to various sorts of matter-energy and information

	Subsystems which process matter-energy		**Subsystems which process information**
3	*Ingestor,* the subsystem which brings matter-energy across the system boundary from the environment	11	*Input transducer,* the sensory subsystem which brings markers bearing information into the system, changing them to other matter-energy forms suitable for transmission within it
		12	*Internal transducer,* the sensory subsystem which receives, from subsystems or components within the system, markers bearing information about significant alterations in those subsystems or components, changing them to other matter-energy forms of a sort which can be transmitted within it
4	*Distributor,* the subsystem which carries inputs from outside the system or outputs from its subsystems around the system to each component	13	*Channel and net,* the subsystem composed of a single route in physical space or multiple interconnected routes over which markers bearing information are transmitted to all parts of the system
		14	*Timer,* the subsystem which transmits to the decider information about time-related states of the environment or of components of the system. This information signals the decider of the system or deciders of subsystems to start, stop, alter the rate, or advance or delay the phase of one or more of the system's processes, thus coordinating them in time
5	*Converter,* the subsystem which changes certain inputs to the system into forms more useful for the special processes of that particular system	15	*Decoder,* the subsystem which alters the code of information input to it through the input transducer or internal transducer into a "private" code that can be used internally by the system
6	*Producer,* the subsystem which forms stable associations that endure for significant periods among matter-energy inputs to the system or outputs from its converter, the materials synthesized being for growth, damage repair, or replacement of components of the system, or for providing energy for moving or constituting the system's outputs of products or information markers to its suprasystem	16	*Associator,* the subsystem which carries out the first stage of the learning process, forming enduring associations among items of information in the system
7	*Matter-energy storage,* the subsystem which places matter or energy at some location in the system, retains it over time, and retrieves it	17	*Memory,* the subsystem which carries out the second stage of the learning process, storing information in the system for different periods of time, and then retrieving it
		18	*Decider,* the executive subsystem which receives information inputs from all other subsystems and transmits to them outputs for guidance, coordination, and control of the system
		19	*Encoder,* the subsystem which alters the code of information input to it from other information processing subsystems, from a "private" code used internally by the system into a "public" code which can be interpreted by other systems in its environment
8	*Extruder,* the subsystem which transmits matter-energy out of the system in the forms of products or wastes	20	*Output transducer,* the subsystem which puts out markers bearing information from the system, changing markers within the system into other matter-energy forms which can be transmitted over channels in the system's environment
9	*Motor,* the subsystem which moves the system or parts of it in relation to part or all of its environment or moves components of its environment in relation to each other		
10	*Supporter,* the subsystem which maintains the proper spatial relationships among components of the system, so that they can interact without weighting each other down or crowding each other		

A set of symbols, shown in figure 2, have been designed to represent the levels, subsystems, and major flows in living systems. They are intended for use in simulations and diagrams and are compatible with the standard symbols of electrical engineering and computer science. They can also be used in graphics and flow charts.

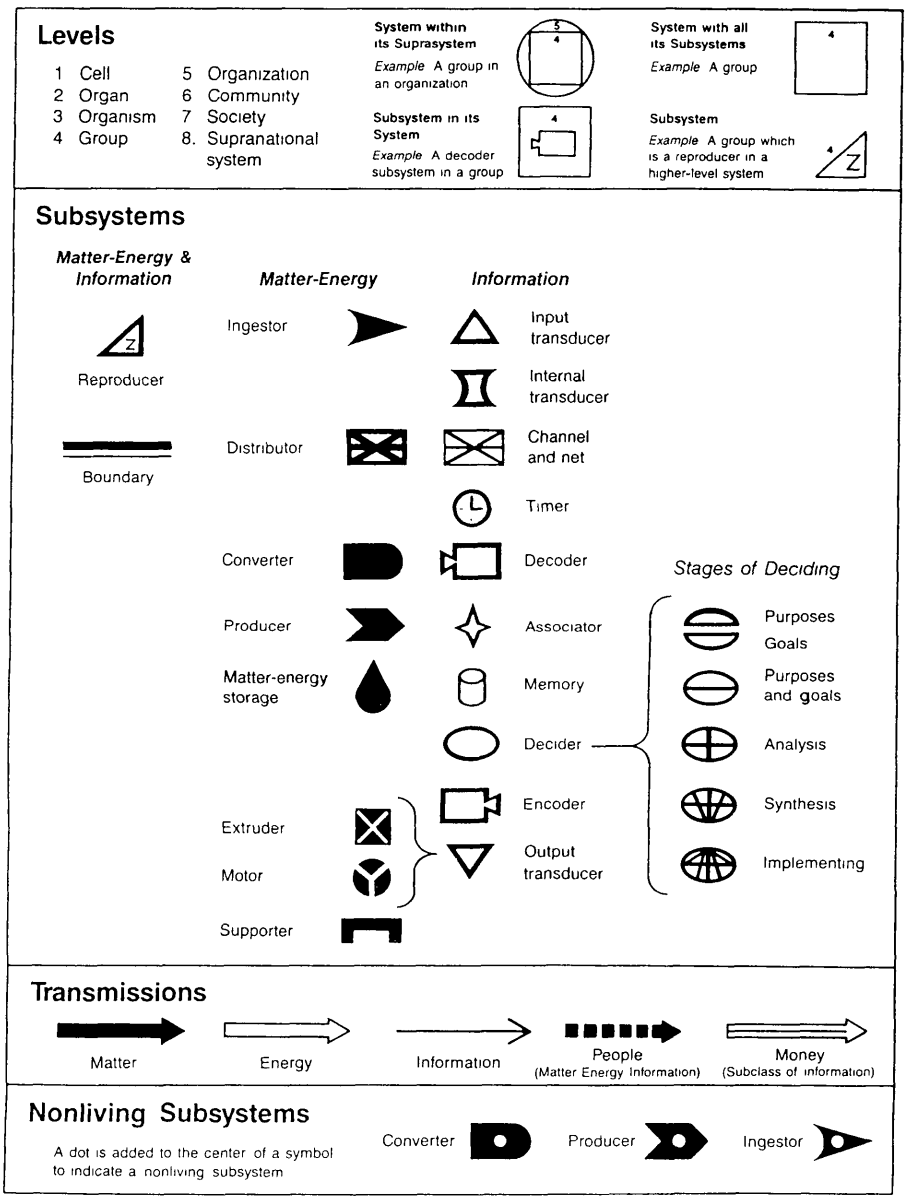


Figure 2

Living Systems Theory Symbols

If a system lacks components for a given subsystem or part of it, it may *disperse* the process to a system at the same or another level. Symbiosis and parasitism are examples. The essential part of the associator subsystem in organizations is downwardly dispersed to human brains, since an organization makes associations only when human subcomponents have done so. An organization may, however, have some components, like a training department, that are involved in the process. It is also possible for

TABLE 2. *Selected Major Components of Each of the 20 Critical Subsystems at Each of the Eight Levels of Living Systems**

Subsystem Level	Reproducer	Boundary	Ingestor	Distributor	Converter	Producer	Matter-energy storage	Extruder	Motor	Supporter
Cell	DNA and RNA molecules	*Matter energy and information* Outer membrane	*Transport molecules*	*Endoplasmic reticulum*	*Enzyme in mitochondrion*	*Chloroplast in green plant*	*Adenosine triphosphate*	*Contractile vacuoles*	*Cilia, flagellae, pseudopodia*	*Cytoskeleton*
Organ	Upwardly dispersed to organism	*Matter-energy and information* Capsule or outer layer	Input artery	Intercellular fluid	Parenchymal cell	Islets of Langerhans of pancreas	Central lumen of glands	Output vein	Smooth muscle, cardiac muscle	Stroma
Organism	Testes, ovaries, uterus, genitalia	*Matter energy and information* Skin or other outer covering	Mouth, nose, skin, in some species	Vascular system of higher animals	Upper gastrointestinal tract	Organs that synthesize materials for metabolism and repair	Fatty tissues	Sweat glands of animal skin	Skeletal muscle of higher animals	Skeleton
Group	NASA officer who selects astronauts for crew	*Matter-energy* Inspectors of covering of spacecraft *Information* Crew radio operator	Astronauts who bring damaged satellite into spacecraft	Crewmember who distributes food	Dispersed to maker of packaged rations	Crewmembers who repair damaged equipment .	Crewmember who stows scientific instruments	Crew that ejects satellite into orbit	Downwardly dispersed to individual members	Crewmembers who maintain spacecraft
Organization	Dispersed upward to society that creates space agency	*Matter energy* NASA inspectors of contracted equipment *Information* NASA guards who arrest intruders	Receiving department of NASA center	Conveyer belt in factory that makes parts for space habitat	Workers who stamp out parts for space vehicle	Doctors who examine astronauts	Workers who store supplies on space vehicle	Janitors in NASA buildings	Driver of gantry crane	Janitors in launch site buildings
Community	Space agency that establishes space station	*Matter-energy* Dispersed to builders of habitat *Information* Operators of downlink to Earth	Receivers of materials from Shuttle	Food servers in dining facility	Organization that mines Moon	Medical organization in space community	Workers who put supplies into storage areas	Mine organization that sends minerals to Earth	Drivers of Moon surface vehicles	Maintenance crew of habitat buildings
Society	Constitutional convention that writes national constitution	*Matter-energy* Customs service *Information* Security agency	Immigration service	Operators of national railroads	Nuclear industry	All farmers and factory workers of a country	Soldiers in Army barracks	Export organizations of a country	Aerospace industry that builds spacecraft	Officials who operate national public buidings and lands
Supranational system	United Nations when it creates new supranational agency	*Matter-energy* Troops at Berlin Wall *Information* NATO security personnel	Legislative body that admits nations	Personnel who operate supranational power grids	EURATOM, CERN, IAEA	World Health Organization	International storage dams and reservoirs	Downwardly dispersed to societies	Operators of United Nations motor pool	People who maintain international headquarters buildings

systems that lack a given process to use an alternative process to accomplish a similar effect. Individual bacteria cannot adapt to the environment by learning, since they lack associator and memory subsystems, but bacterial colonies do adapt by altering the expression of genes. Components of the 20 subsystems at each level of living systems are listed in table 2.

Similar variables can be measured in each subsystem at all levels. These are such things as quantity, quality, rate, and lag in flows of matter, energy, or information.

TABLE 2 *(concluded).*

Subsystem Level	Input transducer	Internal transducer	Channel and net	Timer	Decoder	Associator	Memory	Decider	Encoder	Output transducer
Cell	Receptor sites on membrane for activation of cyclic AMP	Repressor molecules	Pathways of mRNA, second messengers	Fluctuating ATP and NADP	Molecular binding sites	Unknown	Unknown	Regulator genes	Structure that synthesizes hormones	Presynaptic membrane of neuron
Organ	Receptor cell of sense organ	Specialized cell of sinoatrial node of heart	Nerve net of organ	Heart pacemaker	Second echelon cell of sense organ	None found, upwardly dispersed to organism	None found, upwardly dispersed to organism	Sympathetic fiber of sinoatrial node of heart	Presynaptic region of output neuron	Presynaptic region of output neuron
Organism	Sense organs	Proprioceptors	Hormonal pathways, central and peripheral nerve nets	Supraoptic nuclei of thalamus	Sensory nuclei	Unknown neural components	Unknown neural components	Components at several echelons of nervous system	Temporoparietal area of dominant hemisphere of human cortex	Larynx, other components that output signals
Group	Crewmember who receives messages from ground control	Crewmember who reports crew's reactions to life in capsule	Astronauts who communicate person to person	Dispersed to all members who hear time signals	Member who explains coded message	Dispersed to all members who learn new techniques	Dispersed to all crewmembers	Captain of crew in capsule	Members who write reports of space experience	Members who report to Mission Control
Organization	NASA secretaries who take incoming calls	Representative of employees who reports to executive	Users of NASA internal phone network	Office responsible for scheduling flights	Experts who explain specs to contractors	People who train new employees	Filing department	NASA executives, department heads, middle managers	Public relations staff	Administrator who makes policy television speech
Community	Operators of downlink to Earth	Communicator over downlink to Earth	Psychologists who report on morale of spacefarers	Caretakers of clocks in community	Users of communication system in space station	Engineers who interpret building blueprints	Scientists who do research in space	Central computer of space community	Commanding officer and staff	Officer who writes report to Earth station
Society	Foreign news services	Public opinion polling organizations, voters	Telephone and communications organizations	Legislators who decide on time and zone changes	Cryptographers	All teaching institutions of a country	Keepers of national archives	Voters and officials of national government	Drafters of treaties	National representatives to international meetings
Supranational system	UN Assembly hearing speaker from nonmember territory	Speaker from member country to supranational meeting	INTELSAT	Personnel of Greenwich observatory	Translators for supranational meetings	FAO units that teach farming methods in Third World nations	Librarians of UN libraries	National representatives to international space conferences	UN Office of Public Information	Official who announces decisions of supranational body

*Note The components listed in table 2 are examples selected from many possible structures of each subsystem and at each level At the organism level, animals are chosen in preference to plants, although many components of plants are comparable In general, examples are from human rather than animal groups, although similar structures exist in many other species Only human beings form systems above the group Table 2 places special emphasis on living systems involved in space exploration and habitation At each level the examples of subsystem components are from different types of systems This choice makes it clear that the analysis applies to various sorts of systems At the level of the group and above, components involved in communications rather than monetary flows are used as examples in information processing subsystems This is done because monetary flows, while obviously important, are found only in human systems and are currently not very significant in space habitations

8. Adjustment Processes

Living systems of all kinds exist in an uncertain environment to which they must adapt. Excesses or deficits of necessary matter-energy or information inputs can stress them and threaten their continued well-being or even their existence. In the midst of flux, they must maintain steady states of their innumerable variables.

Each system has a hierarchy of values that determines its preference for one internal steady state rather than another; that is, it has *purposes*. These are comparison values that it matches to information inputs or internal transductions to determine how far any variable has been forced from its usual steady state. A system may also have external *goals*, such as finding and killing prey or reaching a target in space.

All living systems have *adjustment processes*, sometimes called "coping mechanisms," that they can use to return variables to their usual steady states. These are alterations in the rates or other aspects of the flows of matter, energy, and information. Subsystems also match the state of each variable they control with a comparison signal and use adjustment processes to correct deviations from it. In general, more adjustment processes are available to higher level systems than to those at lower levels.

Countless small adjustments take place continually as a living system goes about its essential activities. Minor deviations can often be corrected by a single component of one subsystem. More serious threats are countered by a greater number of subsystems or all of them. Severe deviations from steady state constitute pathology that a system may not be able to correct.

The six classes of adjustment processes vary the input, internal, and output processing of matter and energy (matter-energy) and information.

All adjustment processes are used at some cost to the system. Ordinarily a system that survives chooses the least costly of its alternatives.

9. Cross-Level Research

Because of the similarities that exist across all levels of life, empirical cross-level comparisons are possible and are the sort of basic research that is most characteristic of living systems science. Since the evolution of the levels has occurred in physical space-time, their comparable subsystems and variables can ultimately be measured in meter-kilogram-second or compatible units.

Research to test cross-level hypotheses began in the 1950s and continues to the present (Miller 1986a). Such research can provide accurate and dependable fundamental knowledge about the nature of life that can be the basis for a wide range of applications.

LST research strategy: The following strategy is used to analyze systems at any level. It has been applied to systems as different as psychiatric patients and organizations.

1. Identify and make a two- or three-dimensional map of the structures that carry out the 20 critical subsystem processes in the system being studied (see table 2).

2. Identify a set of variables in each subsystem that describe its basic processes. At levels of group and below, these represent aspects of the flows of matter, energy, and information. At levels of organization and above it has proved useful to measure five instead of three flows: MATFLOW, materials; ENFLOW, energy; COMFLOW, person-to-person, person-to-machine, and machine-to-machine communications information; PERSFLOW, individual and group personnel (who are composed of matter and energy and also store and process information); and MONFLOW, money, money equivalents, account entries, prices, and costs—a special class of information.

3. Determine the normal values of relevant variables of every subsystem and of the system as a whole and measure them over time, using appropriate indicators.

The normal values of innumerable variables have been established for human organisms. A physician can make use of reliable tests and measurements and accepted therapeutic procedures to discover and correct pathology in a patient. Similar information is not available to the specialist who seeks to improve the cost-effectiveness of an organization. Studies that make it possible to generalize among organizations are few, with the result that the usual values of most variables are unknown at organization and higher levels. This lack makes it difficult to determine to what extent an organization's processes deviate from "normal" for systems of its type. Pathology in an organization may become apparent only when deviation is so great that acceptance of the organization's products or services declines or bankruptcy threatens.

4. Take action to correct dysfunctional aspects of the system and make it healthier or more cost-effective, by, for example, removing a psychiatric patient from an unfavorable environment, altering the structure or process of a work group, or introducing nonliving artifacts (like computers or faster transport equipment) into an organization.

Our proposed study would apply the above strategy to evaluating the cost-effectiveness of the operations of a crew of a space station, tracking the five categories of flows through its 20 subsystems, identifying its strengths and dysfunctions, and recommending ways to improve its operations. Later a similar approach could be applied to a mission to Mars, a lunar settlement, and perhaps other human communities in space. It could also be used at Antarctic bases.

Validation of LST: LST arises from the integration of a large number of observations and experiments on systems of a variety of types that represent all eight levels. As with other scientific theories, however, its assertions cannot be accepted without validation.

How have some of the well-known theories been validated? Consider, for example, Mendeleyev's periodic table of the elements, first published in the mid-19th century. In its original form, it was based on a hypothesis that the elements could be arranged according to their atomic weights and that their physical properties were related to their place in the table. Revisions by Mendeleyev and others over succeeding years led to discovery of errors in the assigned atomic weights of 17 elements and included new elements as they were discovered, but the properties of some required that several pairs of elements be reversed. In the early 1920s, after the discovery of atomic numbers, a hypothesis by van den Brock that the table would be correct if atomic number rather than atomic weight were used as its basis was confirmed by H. G. J. Moseley's measurement of spectral lines. The present form of the table places all known elements in correct order and has made it possible to predict the characteristics of elements to be discovered in nuclear reactions.

Confirmation of Mendeleyev's theory required testing of a succession of hypotheses based on it. No theory can be considered valid until such observation and research have shown that its predictions about the real systems with which it is concerned are accurate.

If LST is to have validity and usefulness, confirmation of hypotheses related to it is essential. The first test of an LST hypothesis was a cross-level study of information input overload at five levels of living systems, carried out in the 1950s (Miller 1978, pp. 121-202). It confirmed the hypothesis that comparable information input-output curves and adjustment processes to an increase in rate of information input would occur in systems at the level of cell, organ, organism, group, and organization. Numerous other quantitative experiments have been done on systems at various levels to test and confirm cross-level hypotheses based on living systems theory (e.g., Rapoport and Horvath 1961, Lewis 1981). Such tests support the validity of living systems theory.

Applications of Living Systems Theory

Living systems theory has been applied to physical and mental diagnostic examinations of individual patients and groups (Kluger 1969, Bolman 1970, Kolouch 1970) and to psychotherapy of individual patients and groups (Miller and Miller 1983). An early application of LST at organism, group, and organization levels was a study by Hearn in the social service field (1958).

An application of living systems concepts to families described the structure, processes, and pathologies of each subsystem as well as feedbacks and other adjustment processes (Miller and Miller 1980). A subsystem review of a real family* was carried out in a videotaped interview that followed a schedule designed to discover what members were included in each of several subsystems, how the family decided who would carry out each process, how much time was spent in each, and what problems the family perceived in each process.

Research at the level of organizations includes a study of some large industrial corporations (Duncan 1972); general analyses of organizations (Lichtman and Hunt 1971, Reese 1972, Noell 1974, Alderfer 1976, Berrien 1976, Rogers and Rogers 1976, and Merker 1982, 1985); an explanation of certain pathologies in organizations (Cummings and DeCotiis 1973); and studies of accounting (Swanson and Miller 1989), management accounting (Weekes 1983), and marketing (Reidenbach and Oliva 1981). Other studies deal with assessment of the effectiveness of a hospital (Merker 1987) and of a metropolitan transportation utility (Bryant 1987).

*Personal communication (videotape and script) from R. A. Bell, 1986.

The largest application of LST has been a study of the performance of 41 U.S. Army battalions (Ruscoe et al. 1985). It revealed important relationships between characteristics of matter-energy and information processing and battalion effectiveness.

A research study is being conducted in cooperation with IBM, applying living systems process analysis to the flows of materials, energy, communications, money, and personnel in a corporation, in order to determine its cost-effectiveness and productivity. Discussions of possible use of living systems process analysis to evaluate cost-effectiveness in Government agencies are under way with the General Accounting Office of the United States.

Several researchers (Bolman 1967; Baker and O'Brien 1971; Newbrough 1972; Pierce 1972; Burgess, Nelson, and Wallhaus 1974) have used LST as a framework for modeling, analysis, and evaluation of community mental health activities and health delivery systems. LST has also provided a theoretical basis for assessing program effectiveness in community life (Weiss and Rein 1970).

After a pretest of comparable methods of evaluation, a study of public schools in the San Francisco area was carried out (Banathy and Mills 1985). A more extensive study of schools in that area is now in process under a grant from the National Science Foundation.

The International Joint Commission of Canada and the United States has been using living systems theory as a conceptual framework for exploring the creation of a supranational electronic network to monitor the region surrounding the border separating those two countries (Miller 1986b).

Other applied research studies are in planning stages, and proposals are being prepared for some of them. These include an investigation of how to combine bibliographical information on living systems at the cell, organ, and organism levels by the use of computer software employing living systems concepts; an analysis of insect behavior in an ant nest; and a study of organizational behavior and organizational pathology in hospitals.

The conceptual framework of LST and its implications for the generalization of knowledge from one discipline to another have been discussed by many authors (see Miller 1978 and *Social Science Citation Index* 1979 ff.).

It is too early to make a definitive evaluation of the validity of living systems theory. Not enough studies have been carried out and not enough data have been collected. It is possible to say, however, that the theory has proved useful in conceptualizing and working with real systems at seven of the eight levels. Studies at the eighth level, the organ, have not so far been carried out but these will be undertaken in the future. In addition, the general consensus of published articles about the theory has been supportive.

A Proposed LST Space Research Project

It appears probable that the space station that is now in the planning stage at NASA will become a reality in the next few years. It would be a prototype for future nonterrestrial communities—on the Moon and on Mars.

The crew of such a station would include not only astronauts but also technicians and other personnel. They would spend a much longer time in the space environment than crews of space vehicles on previous missions had spent.

Our research method would use LST process analysis to study the space station crew, identify its strengths and dysfunctions, evaluate the performance of personnel, and recommend ways to improve the cost-effectiveness of its operations.

Until the space station is in operation, we would study human activities on modules of a simulated space station. The method used in this phase could later be applied to the space station and eventually to settlements on the Moon or on Mars.

The basic strategy of LST process analysis of organizations is to track the five flows—matter, energy, personnel, communication, and monetary information—through the 20 subsystems and observe and measure variables related to each. Since money flows would probably be unimportant in the early stages of a space station, only the first four are relevant to the first phase of this research. A larger and more permanent space settlement might well have a money economy.

We would measure such variables as rate of flow of essential materials; lags, error rates, and distortion in information transmissions; timeliness of completing assigned tasks; and time and resource costs of various activities.

Data Collection

We plan to collect both subjective and objective data.

Subjective data would consist of responses by personnel to questions about their activities related to the variables under study. Questions would be presented and answered on computer terminals. Responses would be collected in a centralized knowledge base for analysis by a computerized expert system.

In addition to these subjective reports, our research design includes the use of objective indicators or sensors to monitor flows in all subsystems and components and measure them on a real-time basis. A time series of data about them would be transmitted or telemetered to the knowledge base in the computer.

In addition to standard measures of units of energy, quantities of material, bits of information, and the usual personnel records, we plan to make use of a novel technical innovation to monitor the movements of personnel and materials. It consists of badges similar to the ordinary ID badges worn by personnel in many organizations. Each badge contains an infrared transponder in the form of a microchip that, on receipt of an infrared signal from another transponder on the wall, transmits a stream of 14 characters that identifies the person or object to which the badge is attached. With this equipment it is possible to locate in 0.7 sec any one of up to 65 000 persons or materials such as equipment, furniture, weapons, ammunition, or food. If desired, the phone nearest to a person's present location can be rung in another 0.3 sec.

In this way many aspects of processes such as the response time of personnel to questions or commands, the average time spent in various activities, the patterns of interactions among people, and the movement of equipment to different parts of the space station can be measured without unduly disrupting the day-to-day activities of the system.

All the data on the five major flows from questionnaires and objective indicators would be stored in a single computer. Such data could help NASA officials evaluate the effects on space station operations of changes in policy or procedure. In addition, measurements of variables over time make it possible to determine norms for them and to identify deviations that may show either special strengths or dysfunctions. With such information, a computerized expert system can analyze the relationships among the different variables of the five major flows and suggest ways to improve the space station's effectiveness.

Figure 3 is a diagram of the space station showing how the five flows, MATFLOW, ENFLOW, COMFLOW, PERSFLOW, and MONFLOW, might go through its subsystems. The subsystems are identified by the symbols shown in figure 2. Even when only the primary flows of each sort in the space station are superimposed in a diagram like figure 3, they form a very complex pattern.

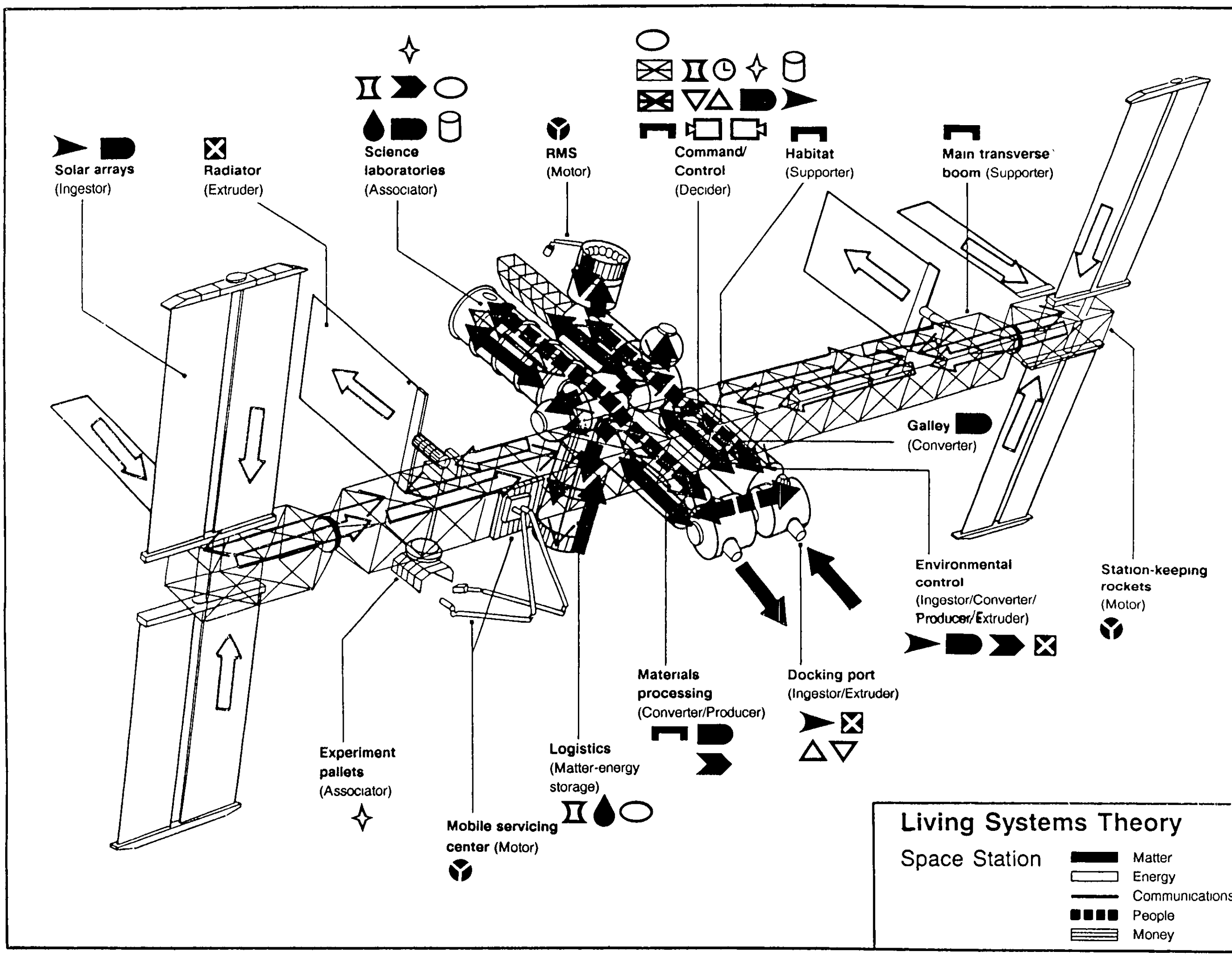


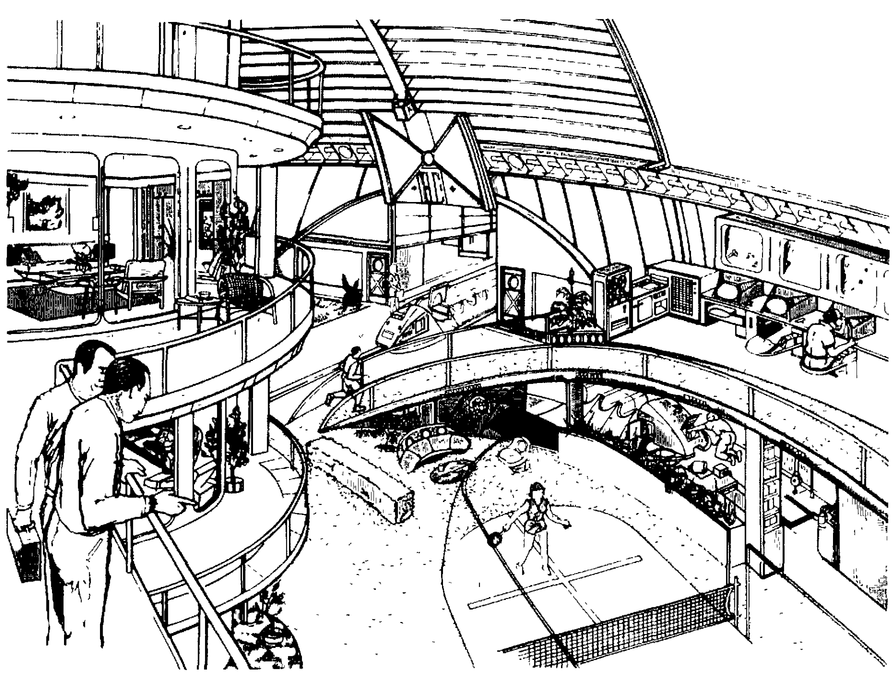
Figure 3

The Five Flows in the Subsystems of the Space Station

In a real space situation, use of monitoring would be of value in many ways. It could identify and report technological or human problems as they occurred. Badges would make it easy for each spacefarer to be found at all times. The officer of the watch would be able to see instantly on a screen the location of all crewmembers with active badges. In addition, the computer could be programmed to present possible solutions to problems and even to initiate necessary steps to assure continuation of mission safety and effectiveness in the event of in-flight emergencies or breakdowns.

Analyzing such flows in subsystems of the space station would provide experience with a novel system for monitoring both living and nonliving components of future space habitations. This experience could well lead to use of similar methods on manned missions to the Moon or to Mars.

For instance, some time in the next century such procedures could be applied to a lunar outpost, a community that would include men, women, and children. A wide range of professional interests, expertise, abilities, and perhaps cultures might be represented in



Monitoring the Movement of People and Equipment at a Space Base

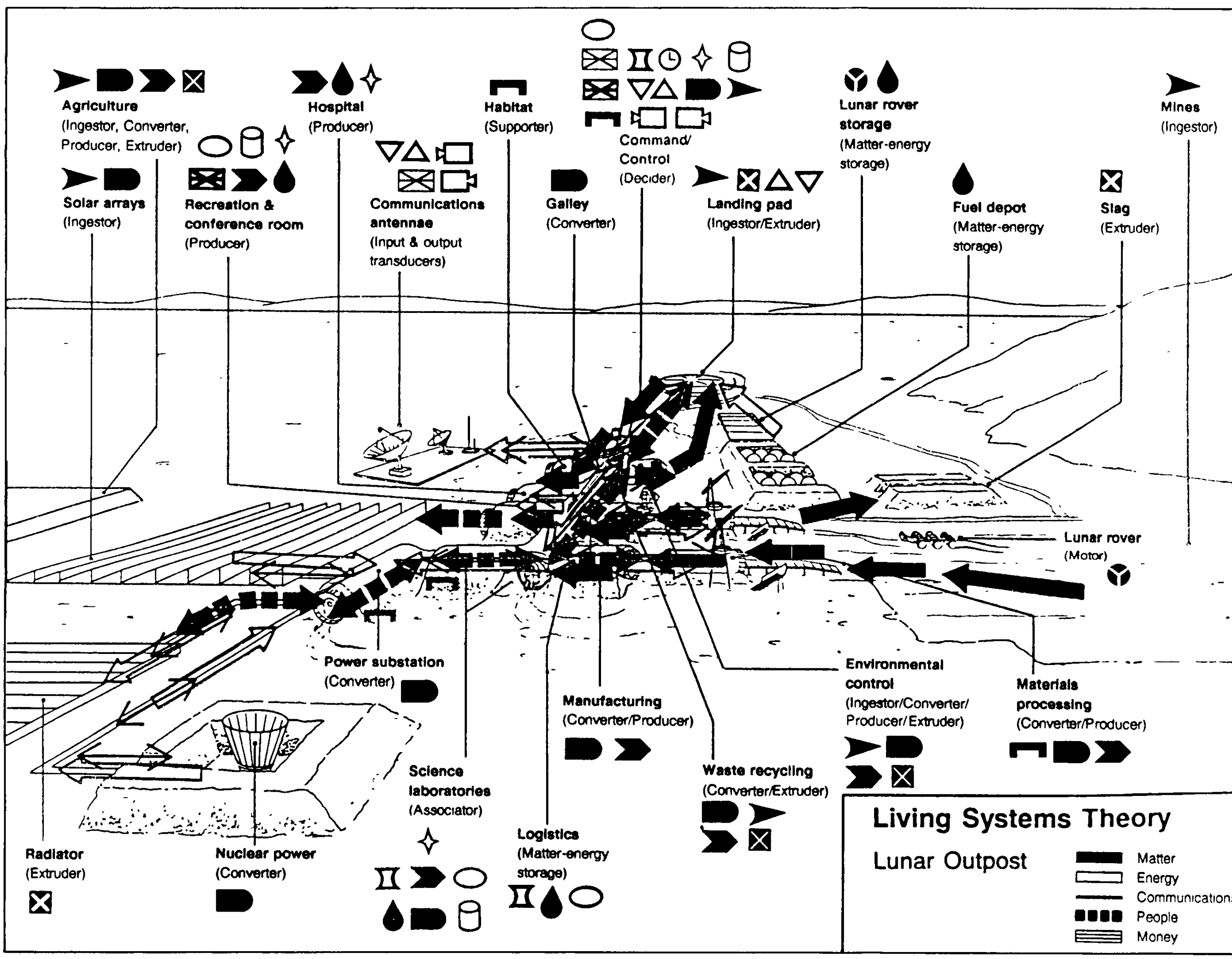
Identification badges containing tiny transponders could track the movements of the woman playing tennis in this space base or the man running on the track. Similarly, property tags with such microchips could report the up-to-the-second location of the monorail train and guard the artwork and plants against theft. Communication of the microchip transponders with transponders mounted on walls would continually report the movements of both personnel and materials to a computerized expert system. If the man servicing the monorail train on the lower level were to get hurt, such automatic monitoring could summon aid in 1 second. And analysis by living systems theory methods could determine whether the interaction between the two men on the walkway is an insignificant waste of time, an important social encounter, or a vital part of an informal communications network.

the lunar community. Residents would live for long times under at least 6 feet of earth or other shielding, which would provide protection from solar radiation, solar flares, and other lunar hazards.

Figure 4 shows such a lunar outpost with designated areas for a command center, habitation, solar power collection, a small nuclear power plant, lunar mines, a solar furnace to use the direct rays of

Figure 4

The Five Flows in the Subsystems of a Lunar Outpost



the Sun for smelting ore and heating the station, a factory, a slag heap, a farm, recycling oxygen and hydrogen, waste disposal, and lunar rovers to transport materials and people on the surface of the Moon from one part of the community to others, as well as for travel outside the immediate area. The five flows through the 20 subsystems of this community are diagramed as were those of the space station shown in figure 3.

Conclusion

The conceptual system and methology of living systems theory appear to be of value to research on life in isolated environments. A space station, which must provide suitable conditions for human life in a stressful environment that meets none of the basic needs of life, is an extreme example of such isolation.

A space station would include living systems at levels of individual human beings, groups of people engaged in a variety of activities, and the entire crew as an organization. It could also carry living systems of other species, such as other animals and plants. Using the subsystem analysis of living systems theory, planners of a station, either in space or on a celestial body, would make sure that all the requirements for survival at all these levels had been considered. Attention would be given not only to the necessary matter and energy (including artifacts such as machinery and implements) but also the equally essential information flows that integrate and control living systems. Many variables for each subsystem could be monitored and kept in steady states.

Use of living systems process analysis of the five flows of matter-energy and information would assure that all members of the crew received what they needed, that distribution and communication were timely and efficient, and that the command centers within the station and on Earth were fully informed of the location and activities of personnel, particularly during an emergency.

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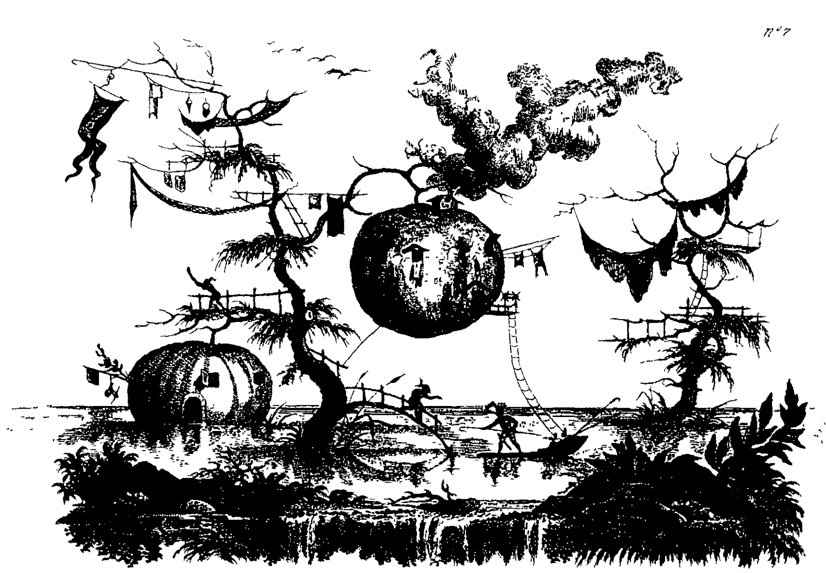
Life Support and Self-Sufficiency in Space Communities

Karl R. Johansson

The development of a controlled ecological life support system (CELSS) is necessary to enable the extended presence of humans in space, as on the Moon or on another planetary body. Over a long period, the provision of oxygen, water, and food, and protection from such inimical agents as radiation and temperature extremes, while maintaining the psychological health of the subjects, becomes prohibitively expensive if all supplies must be brought from Earth. Thus, some kind of a regenerative life support system within an enclosure or habitat must be established, thereby cutting the umbilicus to Mother Earth, but not irreversibly. This protective enclosure will enable the survival and growth of an assemblage of terrestrial species of microorganisms, plants, and animals. I envision that the nonterrestrial ecosystem will evolve through the sequential introduction of terrestrial and local materials, together with the appropriate living forms.

Lunar Characteristics

The principal constraints on life on the Moon are (1) a hard vacuum; (2) apparent lack of water; (3) lack of free oxygen, (4) paucity of hydrogen, carbon, and nitrogen; (5) intense radiation, periodically augmented by solar flares; (6) wide temperature fluctuations at extremes harmful to life; (7) a 2-week diurnal rhythm; and (8) gravity only 1/6 that on Earth.



17th-Century Vision of Life on the Moon

In this fanciful picture of life on the Moon by a 17th-century artist, none of the constraints we now know of are in evidence. The atmospheric pressure appears to be just right for bird flight Water is plentiful. The cloud of smoke testifies to the presence of carbon and oxygen. The hydrogen and nitrogen needed to sustain plant and animal life are apparent in the lush growth, including the pumpkin-like abodes for the human inhabitants and the cloth flags (or is it the wash?) hung out on poles and limbs These inhabitants seem to need no heavy clothing to protect them against hazardous radiation or temperature extremes. Though there may be a long night ahead, this scene seems set in the middle of a long, lazy day. And gravity, though not strong enough to pull a "pumpkin" off a tree, is sufficient to hold the people to the floor of their barge, bridge, or balcony.

Artist: Filippo Morghen

Source of illustration: Library of Congress, Rare Book Division

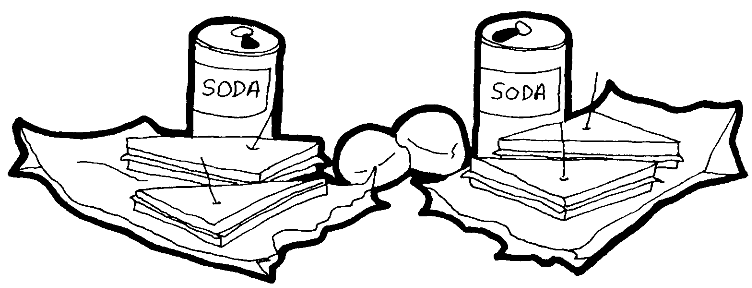
Taken from Davis Thomas, ed., 1970, Moon: Man's Greatest Adventure *(New York: Harry N. Abrams, Inc), p. 69*

Chemistry and Nutrition

Lunar regolith as a cover for the habitat would shield the ecosystem from radiation and from both high and low temperatures. The enclosure would need to be airtight to contain a life-sustaining atmosphere of O_2, CO_2, N_2, and H_2O vapor. Presumably oxygen would be provided through the reductive processing of oxide ores. From a hydrogen reduction process, the product water could be used. With the establishment in the enclosure of photosynthesis by eucaryotes (algae and higher plants), reliance on ore processing for life-support oxygen would diminish, although that capacity should remain in place as a backup. Additional water, as needed, would continue to be provided externally, although the amounts would be small because, in a properly functioning CELSS, all water is recycled and appropriately treated to render it potable (free of infectious or toxic agents).

The lunar regolith could also provide elements implanted there by the solar wind. These elements include hydrogen and carbon, which could be used to manufacture water and carbon dioxide, and gaseous nitrogen (see box). However, the levels of these elements are low (100-150 ppm), and thus their recovery may prove to be uneconomical. In that case, they would have to be transported from Earth until the CELSS matured. Even then, more oxygen, carbon, and nitrogen would need to be introduced into the system periodically as the human and domestic animal population of the habitat increased or as the recycling process became imbalanced. As with oxygen, tanks of compressed carbon dioxide and nitrogen should be on hand to cope with such perturbations. Both air and water would need to be biologically and chemically monitored.

The Moon contains all of the "trace elements" known to be necessary for life; e.g., magnesium, manganese, cobalt, tin, iron, selenium, zinc, vanadium, and tungsten. The trace elements are absolutely critical to all species of life, largely as cofactors or catalysts in the enzymatic machinery. While their diminution would slow down the ecosystem, a sudden flush of certain trace elements known to be toxic above certain concentrations would be detrimental to some of the component species. I hope that the microbial flora which becomes established in the ecosystem will be able to minimize the extent of fluctuation of the trace elements through its collective adsorptive and metabolic functions. This issue will need to be considered in the selection of the microbial species for introduction into the CELSS.



Lunar Lunch

The Moon has been underrated as a source of hydrogen, carbon, nitrogen, and other elements essential to support life. Each cubic meter of typical lunar soil contains the chemical equivalent of lunch for two—two large cheese sandwiches, two 12-oz sodas (sweetened with sugar), and two plums, with substantial carbon and nitrogen left over.

Although no free water has been found on the Moon, its elemental constituents are abundant there. One constituent, oxygen, is the most abundant element on the Moon; some 45 percent of the mass of lunar surface rocks and soils is oxygen. The other constituent, hydrogen, is so scarce in the lunar interior that we cannot claim to have measured any in erupted lavas. Nevertheless, thanks to implantation of ions from the solar wind into the grains of soil on the lunar surface, there is enough hydrogen in a cubic meter of typical lunar regolith to yield more than 1-1/2 pints of water.

Similarly, carbon and nitrogen have also been implanted from the solar wind. The amount of nitrogen in a cubic meter of lunar regolith is similar to the amount of hydrogen—about 100 grams, or 3 percent of the nitrogen in a human body. The amount of carbon is twice that; the carbon beneath each square meter of the lunar surface is some 35 percent of the amount found tied up in living organisms per square meter of the Earth's surface.

All of these elements except oxygen can be extracted from the lunar soil simply by heating it to a high temperature (> 1200°C for carbon and nitrogen), and some oxygen comes off with the hydrogen. Thus, the problem of accessibility of hydrogen, carbon, and nitrogen reduces to one of the economics of heating substantial quantities of lunar soil, capturing the evolved gases, and separating the different gaseous components from each other. Although water could no doubt be extracted from martian soil at a much lower temperature and organic compounds could probably be extracted at a somewhat lower temperature from an asteroid that proved to be of carbonaceous chondrite composition, the Moon is much closer than Mars and its composition is much better known than that of any asteroid.

Collection of even a small fraction of the Moon's budget of hydrogen, carbon, nitrogen, phosphorus, sulfur and other elements essential to life into a suitable environment on the Moon would support a substantial biosphere.

Taken from Larry A. Haskin, 1990, Water and Cheese From the Lunar Desert: Abundances and Accessibility of H, C, and N on the Moon, in The 2nd Conference on Lunar Bases and Space Activities of the 21st Century *(in press), ed. W. W. Mendell (Houston. Lunar & Planetary Inst.).*

Radiation

The surface of the Moon receives from the Sun lethal levels of high-energy electromagnetic radiation, frequently exacerbated by solar flares of varying duration. Without appropriate protection, no living creature, from microbe to man, could survive the onslaught of this radiation. It has been estimated that approximately 2 meters of regolith will absorb this radiation, thereby protecting the human and nonhuman occupants.

Just how much radiation will penetrate various protective shields still needs to be determined. Undoubtedly, radiation-induced mutations will occur; some will be lethal; others may be incapacitating; and still others may result in mutants better able to cope with the lunar environment than the parental organisms. Of particular concern is the likelihood of mutation among many of the microorganisms constituting the ecosystem, thereby endangering the cycling of the critical elements in the lunar CELSS.

Temperature

With proper attire, humans can withstand, at least for short periods, temperature extremes as high as 50°C and as low as -90°C. The extremes on the Moon exceed these limits by a wide margin. Moreover, other species within the CELSS module would be either killed or suppressed by such extreme temperatures. Obviously, the temperature of a CELSS must be maintained within a moderate range, such as 15 to 45°C, to enable the growth and reproduction of living forms. While many types of psychrophilic and thermophilic microorganisms abound on Earth, their introduction into the CELSS would be useless because neither the food crops to be grown therein nor the human beings harvesting those crops can withstand the temperatures they require.

Regulation of the temperature within a CELSS must take into account radiant energy from the Sun and the release of energy from biological and mechanical activity within the confines of the habitat. The former can be minimized by the protective blanket of regolith required for radiation protection. Efflux of heat from the interior of the habitat may require provision of active or radiative cooling.

Energy for Life

All living forms require an adequate food supply and a source of energy. Among animals and humans, energy is derived from the metabolism of various organic constituents of the diet; e.g., carbohydrates, lipids, proteins, and other nutrients. While many microorganisms gain energy (and carbon) from the oxidation of organic compounds, including methane, many also derive energy from the oxidation of reduced inorganic compounds; e.g., sulfides, ammonia, nitrites, Fe^{++}, and hydrogen. Photosynthetic forms of life (some bacteria, the algae, and the higher plants) can convert photons of energy into chemical bond energy with the photolysis of water and the evolution of molecular oxygen. The energy thus realized is used in the synthesis of carbohydrate (from carbon dioxide and water), which the plants can further metabolize to meet their needs or which can be eaten by animals and humans to supply their energy needs.

It is clear that the requirements for food and energy are interrelated and that the various metabolic processes in the complex food chain affect the availability of nutrients to all the species. Light is a particularly important source of energy because the process of photosynthesis must go on in order for molecular oxygen, required by all but the anaerobic forms of life (principally bacteria), to be regenerated from water. It will probably be necessary, however, to regulate the light synchrony if crop production is to be successful, because 2 weeks of dark and 2 of light will not enable normal plant growth, though special strains might be developed. At the poles, perpetual sunlight could probably be obtained on selected mountains, thus enabling an Earth-like photocycle to be created by periodic blocking of the sunlight (see fig. 5). Elsewhere, artificial light will have to be used to break up the 2-week night.

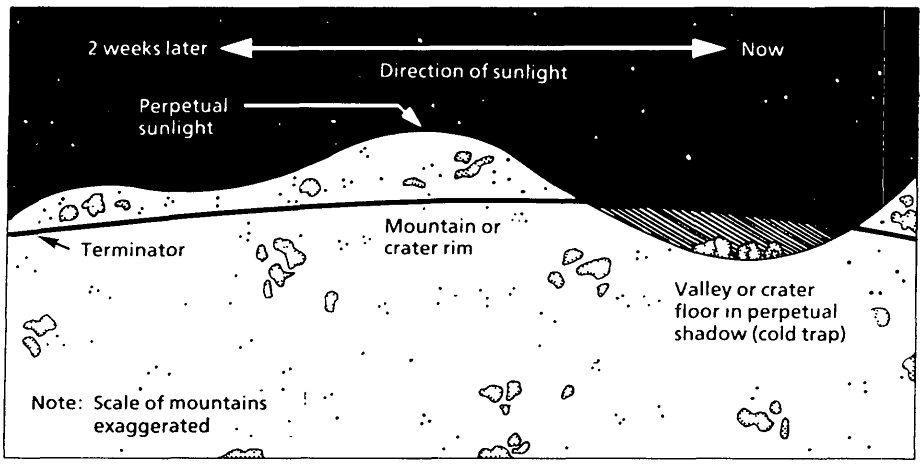
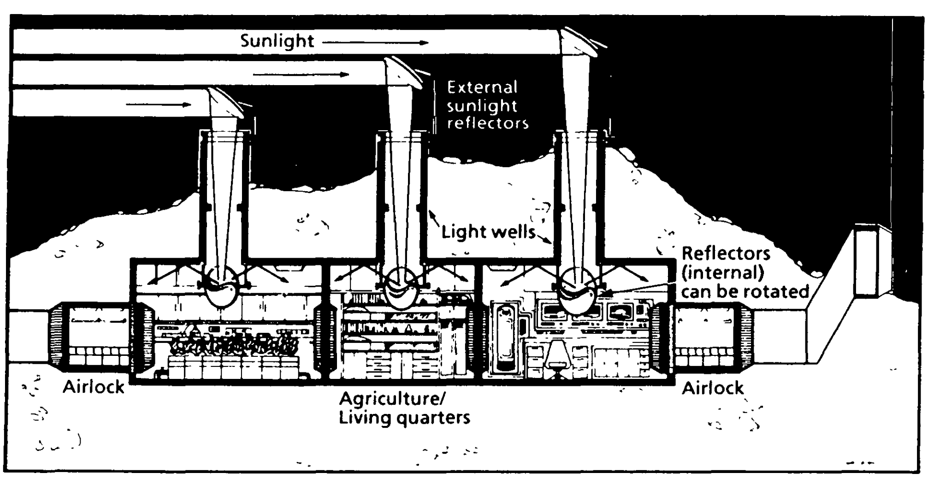


Figure 5

a. Lunar Polar Illumination

The Moon's diurnal cycle of 14 Earth days of sunlight followed by 14 Earth days of darkness could be a problem for siting a lunar base dependent on solar energy or cryogenic storage. A site that might obviate this problem would be at one of the lunar poles. At a pole, high points, such as mountain tops or crater rims, are almost always in the sunlight and low areas, such as valleys or crater floors, are almost always in the shade. The Sun as seen by an observer at the pole would not set but simply move slowly around the horizon. Thus, a lunar base at a polar location could obtain solar energy continuously by using mirrors or collectors that slowly rotated to follow the Sun. And cryogens, such as liquid oxygen, could be stored in shaded areas with their constant cold temperatures.



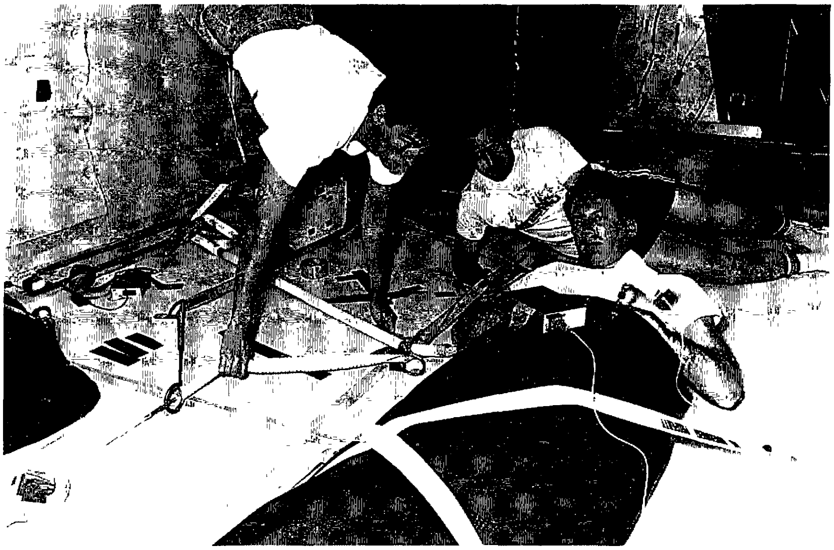
b. Polar Lunar Base Module

Light could be provided to a lunar base module located at the north (or south) pole by means of rotating mirrors mounted on top of light wells. As the mirrors tracked the Sun, they would reflect sunlight down the light wells into the living quarters, workshops, and agricultural areas. Mirrors at the bottom of the light wells could be used to redirect the sunlight or turn it off.

Gravity

Investigations of the effects of reduced gravity (0.167 g on the Moon) on human physiology and performance and on fundamental life processes in general are being supported and conducted by NASA. Astronauts from the Apollo and other short-term space missions have experienced the well-known, and reversible, vestibular effect (motion sickness) and cephalic shift of body fluids (facial puffiness, head congestion, orthostatic intolerance, and diminution of leg girth). (See figure 6.) Longer-term weightlessness, as experienced by the Skylab astronauts and the Salyut cosmonauts, is more complex, resulting in cardiovascular impairment, atrophy of muscle, reduction in bone mass through osteoporosis (loss of calcium), hematologic changes (leading to immunosuppression and diminished red blood cell mass), neuroendocrine perturbations, and other pathophysiological changes. Some of these effects may be minimized by routine exercise, and apparently all are reversible, in time, upon return to 1 g. The response of plants, microorganisms, and "lower forms" of animal life to micro- or zero gravity has been investigated on Skylab, on Space Shuttle missions (see fig. 7), and in simulations on Earth, during parabolic flight of aircraft or in a "clinostat." Unless humans and other life forms can adapt to zero g, or to low g as on the Moon or Mars, it may be necessary to provide rotating habitats to achieve the desired gravitational force, as many authorities have long proposed.

Figure 6



Lower Body Negative Pressure Device

Principal Investigator John Charles tries out the lower body negative pressure device on a parabolic flight of the KC-135, while its designer, Barry Levitan, looks on from behind him, with project engineer Pat Hite on the side. This accordion-like collapsible version of a device used on Skylab creates a vacuum that pulls the subject's blood into the lower half of the body, just as if the person had suddenly stood up. Its purpose is to prepare the astronaut for return from weightlessness to Earth's gravity and keep that person from blacking out. Mission Specialists Bonnie Dunbar and David Low tested the lower body negative pressure device, which was fabricated at the Johnson Space Center, on Space Shuttle flight 32, January 9-20, 1990.

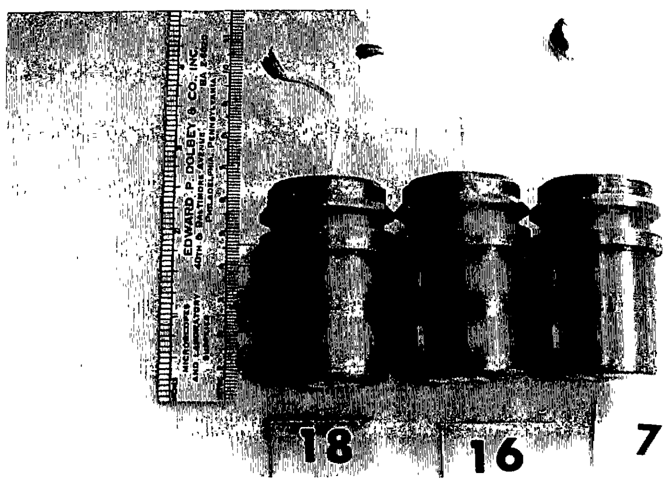


Figure 7

Seedlings Grown on Spacelab 1

These seedlings of Helianthus annuus *(dwarf sunflowers) were planted by Payload Specialist Ulf Merbold for Heflex, the Helianthus Flight Experiment, conducted in Spacelab 1. Upon being removed from the gravity-inducing centrifuge on which they had sprouted and being placed in microgravity, these seedlings continued to circumnutate, thus proving that Charles Darwin was right in thinking that this spiral growth process is intrinsic to plants, not a response to gravity. The curvature of the seedlings is their response to gravity upon return to Earth at the end of Space Shuttle flight 9, November 28-December 8, 1983*

Heflex is part of an ongoing study of plant response, which will continue in IML-1, the International Microgravity Lab, to be flown on the Space Shuttle in 1991. In two experiments in the part of IML-1 called the Gravitational Plant Physiology Facility, scientists will try to determine the threshold at which oat seedlings can detect gravity and the threshold at which wheat seedlings respond to blue light in the absence of gravity.

Photo: David K. Chapman, Co-Investigator

Selection of Species for an Ecosystem

The greatest challenge in the ultimate establishment of a true space habitat is the creation of a functioning, reliable ecosystem, free, insofar as possible, of pathogens, noxious plants, venomous insects, etc. Moreover, the integrity of a working ecosystem would need to be preserved and its functions monitored regularly.

While it is easy to propose the inclusion of particular species of bacteria, fungi, algae, and higher plants, each of which performs a particular biochemical function in the recycling of nutrients, no rationale exists by which one can predict which particular combination of species would be compatible under the conditions extant in the lunar environment. Considerably more research must be done on closed and semi-closed ecosystems before the organisms for a lunar CELSS are selected (see fig. 8). Conceivably, any number of combinations of species may be found to work well. One point must be stressed: More than one species of organism must be selected to carry out each particular function. Thus, several species of photosynthetic, nitrogen-fixing, nitrifying, or sulfur-oxidizing bacteria must be included. Likewise, a number of species of algae and higher plants, each with the common characteristic of being photosynthetic, must be introduced into the community. Such redundancy, which exists to a vast degree on Earth, provides a kind of buffer in case some of the species lose their niches in the ecosystem and die.

Figure 8

Zeoponics Plant Growth Chamber at NASA's Johnson Space Center

In this step toward a controlled ecological life support system (CELSS) for a lunar base, plants are being grown in varying mixtures of zeolite and quartz sand (Zeolite is an aluminosilicate mineral that is able to freely exchange constituent ions with other ions in solution without any apparent change in its mineral structure.) Wheat plants (soft red winter wheat, Coker 68-15) have shown the most favorable response in zeoponics systems consisting of 25 to 75 percent zeolite compared to other zeolite treatments and a commercial potting soil. This research is being conducted by Doug Ming and Don Henninger.

Some Special Aspects of Life in the CELSS

In the first place, the smaller the CELSS, the more magnified becomes any biological, chemical, or physical aberration. No doubt human occupants of the first CELSS module would need more help from the outside at the beginning than they would later on, when numerous connected modules were in place.

The dieback of some support species may well occur from time to time. This would need to be monitored, so that appropriate measures could be taken to reintroduce another strain of the lost species or to introduce an entirely different species with comparable biochemical properties. Reasons for loss of a species in an artificial ecosystem include (1) mutation, (2) temporary tie-up of a critical nutrient, (3) a flush of toxic ions or compounds, (4) malfunction of the temperature control system, (5) a sudden shift in the synchrony of food cycling, and (6) infection or toxemia. The last reason may be particularly troublesome since it will not be possible to assure the exclusion of infectious or toxic microorganisms from the habitat. Many members of the body's normal microflora are opportunistic and can, under certain circumstances, cause disease. Also, plant diseases may emerge if care is not exercised in the initial entry of seeds or of other materials which may contain plant pathogens.

Any animals (e.g., chickens, goats, dwarf pigs) ultimately selected for the space habitat should have been raised in a pathogen-free environment on Earth and tested thoroughly for the presence of any microbial pathogens before their introduction. Gnotobiotic ("germ-free," devoid of a microflora) animals, however, should not be considered because upon exposure to the nonsterile environment of the CELSS they would undoubtedly die of overwhelming infections; such animals have very immature immune systems.

Humans chosen to occupy the CELSS should be protected against certain infectious diseases (e.g., poliomyelitis, measles, whooping cough, and typhoid fever) and bacterial toxemias (e.g., tetanus, diphtheria, and perhaps botulism) by the administration of appropriate vaccines and toxoids. While it would not be possible to assure the total lack of serious pathogenic microorganisms in the human inhabitants, all candidates should be checked microbiologically to assess their carrier state.

The very potent tool of genetic engineering no doubt will be useful in establishing strains of microorganisms or plants with special properties, making it possible to introduce (1) better food crops, (2) organisms with special metabolic functions, and (3) disease-resistant plants.

While this treatise is directed at a lunar ecological system, it is worth noting that a laboratory in low Earth orbit or one in a modified external tank placed in orbit by a Space Shuttle offers certain advantages over the lunar environment as a place to establish and study space ecosystems for application elsewhere, as on Mars, where water and carbon dioxide exist in relative abundance.

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Human Safety in the Lunar Environment

Robert H. Lewis

Any attempt to establish a continuously staffed base or permanent settlement on the Moon must safely meet the challenges posed by the Moon's surface environment. This environment is drastically different from the Earth's, and radiation and meteoroids are significant hazards to human safety. These dangers may be mitigated through the use of underground habitats, the piling up of lunar material as shielding, and the use of teleoperated devices for surface operations.

The Lunar Environment

The Moon is less dense than the Earth and considerably smaller. Its density indicates that the Moon's bulk composition is also somewhat different from Earth's, although it is still a terrestrial (rocky) body. The Moon's surface gravity is only one-sixth the Earth's. And, with its consequently lower escape velocity, the Moon cannot maintain a significant atmosphere. Thus, the surface is directly exposed to the vacuum of space. Lacking an atmospheric buffer, the Moon has a surface temperature that varies over several hundred degrees Celsius during the course of a lunar day/night cycle. A complete lunar day, one full rotation about its axis, requires approximately 27-1/3 terrestrial days.

Compared to the Earth, the Moon is geologically inactive. Volcanism and internally generated seismic activity are almost nonexistent. Furthermore, water and atmospheric processes are unknown on the Moon. Other than igneous differentiation, which occurred early in lunar history, the main geological process that has acted on the Moon is impact cratering.

The Moon was heavily bombarded by meteoroids throughout much of its early existence. Evidence from the Apollo expeditions suggests that the bombardment decreased significantly about 3.8 billion years ago. This early bombardment and subsequent impacts during the past 3.8 billion years have pulverized the lunar surface into dust and small fragments of rock, a layer referred to as the lunar "regolith." The majority of the Moon's surface is made up of heavily cratered terrain, rich in the mineral plagioclase feldspar and known as the lunar "highlands." The uncompacted, upper portion of the highlands' regolith is 10 to 20 meters deep in most places. A smaller portion of the lunar surface, mostly on the Earth-facing side, consists of basaltic lava flows and is known as the lunar "maria." The maria are geologically younger than the highlands and thus have been cratered far less than the highlands have. The depth of uncompacted regolith in the maria is roughly 4 to 5 meters.

The bulk density of lunar regolith increases with depth. Its upper surface is believed to have 45-percent porosity (Taylor 1982, p. 119). The porous upper 20 cm of the regolith results from repeated meteoroid impacts, which stir up the exposed surface and occasionally form large craters. These meteoroids represent potential hazards to both manned and unmanned activities. The meteoroid hazard on the lunar surface may be greater than that in free space (Mansfield 1971, p. 1-4-14). In addition to the free-space flux of meteoroids, there is also ejecta from the impacts. Some fragments of ejecta could have larger masses and slower velocities than the free-space population of meteoroids.

The Moon's surface is exposed to three types of hazardous ionizing radiation. The first two, the solar wind and solar flares, are produced by the Sun. The third type has its origin outside the solar system and is known as galactic cosmic rays.

The solar wind is an isotropically distributed, neutral plasma travelling at an average velocity of 400 km/sec. In Earth/Moon space, it has an average density of about 10 particles per cubic centimeter (Taylor 1982, p. 155). This plasma is composed of a relatively constant flux of charged particles, mainly electrons and protons, plus ions of various elements.

A solar flare is similar in composition to the solar wind, but its individual particles possess higher energies. A solar flare may be considered a transient perturbation in the solar wind. Exact timing of the occurrence of a flare is difficult to predict, but the frequency of flares may be related to the 11-year solar cycle. Most flares can be observed at the Sun's surface some time before a large increase in the solar wind's higher energy particles is detected in the vicinity of the Moon. Not all solar flares yield particles that reach the Earth/Moon vicinity, but, of those which do, this flux reaches a peak within hours and then decreases over several days to the previous solar wind level.

Galactic cosmic rays are apparently isotropically produced outside the solar system. The average cosmic ray flux has been almost constant over the past 50 million years (Taylor 1982, p. 159). Cosmic rays are made up of very high energy particles consisting mostly of protons and electrons, plus some heavy nuclei (iron, for example), positrons, and gamma rays. Both the Earth and the Moon are exposed to these cosmic rays, but the Moon's surface receives a higher intensity of cosmic rays than does the Earth's surface.

The Earth's magnetic field and atmosphere provide significant protection, lacking on the Moon. The cosmic ray flux per square centimeter of lunar surface per year (during minimum solar activity) contains 1.29×10^8 protons plus 1.24×10^7 helium nuclei plus 1.39×10^6 heavier ions for a total of 1.4279×10^8 particles per cm^2 per year.* Fortunately, as the energy of the radiation increases from solar wind to cosmic rays, the frequency of encountering that radiation decreases.

*Counting only particles with a velocity greater than 10 MeV per nucleon. Information from D. Stuart Nachtwey, Medical Sciences Division, Lyndon B. Johnson Space Center, Houston.

Lunar Public Works

The dry, barren Moon might not seem like a promising land for settlement. But, with the eyes of a chemist, a pioneer settler may see lunar conditions as advantages and lunar soil as a bountiful resource

Lunar Water Works

The first concern of a lunar pioneer must be water. There may or may not be water, as trapped ice, at the lunar poles, but there certainly is an abundance of its chemical components, oxygen and hydrogen. Oxygen is the most abundant chemical element (45% by weight) in the lunar soils, from which it may be extracted by various processes. In contrast, the concentration of hydrogen in lunar soil is very low, but the total quantity available is nevertheless great. The lunar surface has been bathed for billions of years in the solar wind, a flux of ionized atoms from the exterior of the Sun. These ions embed themselves in the surface of grains of lunar topsoil. Furthermore, meteorites, unimpeded by an atmosphere, continually plow under the old solar-wind-rich grains and expose new grains. In this way, large amounts of hydrogen have become buried in the soil, enough to produce (if combined with lunar oxygen) about 1 million gallons (3.8 million liters) of water per square mile (2.6 km^2) of soil to a depth of 2 yards (1.8 m). This hydrogen can be extracted by heating the soil to about 700°C Supplying the Lunar Water Works is a matter of technology and economics, but not a matter of availability of oxygen and hydrogen on the Moon.

Lunar Community Farm

The next concern of a lunar pioneer will be food. Like hydrogen, carbon and nitrogen are available in large quantities from the lunar soil, although they are present in very low concentrations, having been placed there, like hydrogen, by the solar wind. All the other nutrients necessary to life are likewise present in the soil. Pioneer settlers should be able to obtain these elements by heating the soil. Once people have provided them with lunar water, carbon dioxide, oxygen, and nitrogen, plants should be able to extract nutrients directly from the lunar soil.

Lunar Filling Station

The lunar covered wagon will be a chemical rocket, its horsepower hydrogen and oxygen. Hauling these propellants from Earth will be expensive. It may prove cheaper to provide them from the lunar soil. Forty tonnes of hydrogen, a reasonable estimate of the amount needed for all transportation from low Earth orbit for a year, could be obtained from just 0.3 km^2 of soil mined to a depth of 1 m. Alternatively, lunar transport vehicles might burn a metal such as iron, aluminum, or silicon, even though these are less efficient rocket fuels than hydrogen. All three are major constituents of lunar soils, in chemical combination with oxygen, from which they can be extracted. In fact, each is a byproduct of one or more processes for producing oxygen. [Several techniques for extracting oxygen from lunar soils are proposed in the Materials *volume of this* Space Resources *report.]*

Lunar Lumberyard

Better than burning the iron, aluminum, and silicon produced as byproducts of oxygen extraction from lunar soils might be to use them to construct lunar shelters. Iron and aluminum can be fabricated into beams. The boards of space construction may well be made of glass. Molten lunar soil can be cast into silicate sheets or spun into fiberglass. These may have greater strength than similar products on Earth because of the lack of water to interfere with their polymer bonds. Partially distilled in a solar furnace, soil residue may take on the composition of a good cement, which when combined with locally produced water and the abundance of aggregate would become concrete. [These manufacturing processes are also discussed in the accompanying Materials *volume.] The unprocessed soil itself can serve as shielding against the diurnal temperature fluctuations and, more importantly, against the hazards of radiation unscreened by an atmosphere and undeflected by a magnetic field, as discussed by Rob Lewis in this paper.*

Lunar Light and Power

The Sun shines on the Moon plentifully and predictably, but only half the time. Storing solar energy over the 2-week-long lunar night seems difficult and may have to be done in the form of hydrogen, metals, and oxygen whose extraction was powered by energy from the Sun. Thus, initially, lunar power is likely to come from an imported nuclear power plant. But electrical power derived from the Sun is a likely lunar product and may even be the first major export to the Earth from the Moon (once the souvenir market has been satisfied). Eventually, the solar cells will probably be derived from lunar silicon, a byproduct of oxygen extraction, or from lunar ilmenite, recently shown to be photovoltaic. Conversion need not be efficient if a local material, simply obtained. is used as the photovoltaic. More futuristically lunar helium-3 has been proposed for use as a fusion fuel superior to tritium in that it is not radioactive. does not have to be made in nuclear fission reactors, and yields a proton instead of a more destructive neutron when it fuses with deuterium.

Lunar soil contains in abundance the materials required for life support, transportation, construction, and power. With proper understanding and new ideas, lunar pioneers should be able to turn the lunar environment to their advantage.

Taken from Larry A. Haskin and Russell O. Colson, 1990, Lunar Resources—Toward Living Off the Lunar Land, in Proc. 1st Symp. NASA/Univ. of Arizona Space Engineering Research Center (in press), ed Terry Triffet (Tucson).

The Human Factor

In order to develop permanent human settlements on the Moon, we must understand how the local environment influences the settlers' safety and health. The lack of atmosphere and the extreme temperature range mandate the use of sealed and thermally insulated enclosures. These enclosures—the colonists' first line of defense—will range from individual space suits to buildings. The next line of defense must protect the colonists from both meteoroids and radiation.

Meteoroid impacts may have effects ranging from long-term erosion of the surface materials of pressure vessels and space suits all the way to penetration and subsequent loss of pressure and injury to personnel (see fig. 9). More serious impacts could result in destruction of equipment and loss of life.

Figure 9

Crisis at the Lunar Base

A projectile has penetrated the roof of one of the lunar base modules and the air is rapidly escaping. Three workers are trying to get into an emergency safe room, which can be independently pressurized with air. Two people in an adjoining room prepare to rescue their fellow workers. The remains of the projectile can be seen on the floor of the room. This projectile is probably a lunar rock ejected by a meteorite impact several kilometers from the base. A primary meteorite would likely be completely melted or vaporized by its high-velocity impact into the module, but a secondary lunar projectile would likely be going slowly enough that some of it would remain intact after penetrating the roof. Detailed safety studies are necessary to determine whether such a meteorite strike (or hardware failure or human error) is likely to create a loss-of-pressure emergency that must be allowed for in lunar base design.

Artist: Pamela Lee


CAPACITY 3
SAFE ROOM
EMERGENCY

In 1971, the Rockwell Lunar Base Synthesis Study investigated several strategies for dealing with the meteoroid hazard. They took a probabilistic approach to the problem of safety and examined several options. Rockwell was interested in providing portable shielding for short-term surface activities as well as more permanent fixed shielding. The shielding might be needed many times during an expedition covering large distances.

On Earth, mobile expeditions which require temporary environmental protection that is lightweight and easy to redeploy often use tents. The Rockwell study examined the use of a tent-like structure which could be erected over an inhabited pressure vessel. The tent could be constructed of a lightweight material such as aluminum foil or nylon. The Rockwell investigators anticipated that such a structure would act as an extra outer layer of protection against meteoroid impact. For their calculations, the tent had an area of 46 m^2 and the insulated wall of the pressure vessel had a density of approximately 8 kg/m^3. A small gap between the tent and pressure wall was initially considered. This arrangement could provide a 0.9999 probability of no penetrations in 100 days if only a free-space meteoroid flux was assumed. However, assuming also the secondary ejecta hazard, they found that the tent system had only a 0.1 probability of not being penetrated within 100 days. A logical next step would be to add more layers of material to the tent. This, of course, increases the weight of the tent and its associated transportation costs.

The next option that Rockwell considered was identical to that just described but with an additional layer of material filling the gap. In theory, the tent would serve to fragment a meteoroid and the underlying material would impede and absorb the fragments before they reached the pressure vessel. On the basis of their surface meteoroid flux model, the gap filler would need to have a density of 16 kg/m^3 to provide a 0.9999 probability of no penetration within 100 days. A design of this type may prove to be practical as portable meteoroid shielding for short-term surface activities.

However, these measures would be completely inadequate for any long-duration habitat (for a stay of over 100 days), so the addition of shielding material seemed desirable. If lunar regolith were used as a gap filler, significant protection could be added without increasing transport costs from Earth. Rockwell concluded that a gap of approximately 15.2 cm (6 inches), filled with lunar regolith, would reduce the penetration risk to less than one chance in 10 000 over a 2- to 5-year stay.

Although meteoroid impacts may be a serious problem on an infrequent basis, the effect of ionizing radiation on human health is continuous and cumulative over an individual's lifetime. A brief discussion of radiation dosimetry is now in order. The fundamental unit of radiation transfer is the *rad*; 1 rad represents the deposition of 100 ergs of energy in 1 gram of mass. The characteristics of the deposition mechanisms vary and additional factors must be considered. One conversion factor is the quality factor, Q, which is conservatively based on the experimentally determined relative biological effectiveness, RBE. When Q is multiplied by the rad exposure, the result is a unit of dosage corrected for the type of radiation; this resulting dosage is measured in a unit known as the *rem*.

Individual responses to radiation exposure vary somewhat and there is controversy over safe limits for long-term, low-level exposures. Currently, the maximum permissible whole-body dose for radiation workers is 5 rem/year and for the general public 0.5 rem/year (CRC Handbook of Tables for Applied Engineering Science 1980, p. 753). Both of these doses are larger than the dose of background radiation at sea level that humans are normally exposed to. Just as radiation workers must accept a greater risk than do members of the general public, so astronauts are prepared to accept a greater risk than radiation workers. Table 3, provided by Stu Nachtwey, lists the doses and health risks that the Medical Sciences Division at the Johnson Space Center estimates an astronaut on a Mars or lunar base mission would be exposed to during a period of minimum solar activity.

TABLE 3. *Approximate Radiation Doses and Health Risks for an Astronaut on a Mars or Lunar Base Mission During Minimum Solar Activity*
[From D. Stuart Nachtwey, Johnson Space Center]

Radiation source	Representative shielding	Skin dose equivalent	Deep organ (5 cm) dose equivalent	Excess lifetime cancer incidence in a 35-year-old male*
Chronic exposure				
Trapped belts (one-way transit)	2 g/cm^2 Al	< 2 rem	< 2 rem	< 0.1%
Free space	4 g/cm^2 Al	75 rem/yr	53 rem/yr	~ 1.2%/yr of exposure
On lunar surface	4 g/cm^2 Al	38 rem/yr	27 rem/yr	~ 0.6%/yr of exposure
On martian surface	16 g/cm^2 CO_2 (atm.)	13.2 rem/yr	12 rem/yr	~ 0.3%/yr of exposure
Acute exposure to large (e.g., Aug. '72) solar particle event				
Free space	2 g/cm^2 Al	1900 rem	254 rem	~ 5.7%
On lunar surface	4 g/cm^2 Al	440 rem	80 rem	~ 1.8%
+ shielding	15 g/cm^2 Al	19 rem	9 rem	~ 0.2%
On martian surface	16 g/cm^2 CO_2 (atm.)	9 rem	4.6 rem	~ 0.1%
+ shielding	60 g/cm^2 Al	< 1 rem	< 1 rem	< 0.03%

*The excess cancer incidence for a 35-year-old female is roughly twice that for a 35-year-old male

The rate of irradiation per unit time and the age and sex of the individual at irradiation are also important. Younger people are more sensitive to the cancer-inducing effects of radiation than older people, and females are more sensitive than males because of cancer induction to the breast and thyroid. Other serious radiation effects include cataracts, genetic damage, and death. Radiation exposure is considered cumulative over an individual's lifetime.

Solar flares and cosmic rays are the most dangerous radiation events that lunar pioneers will be exposed to. The cosmic ray dosage at the lunar surface is about 30 rem/year and, over an 11-year solar cycle, solar flare particles with energies greater than 30 MeV can deliver 1000 rem (Silberberg et al. 1985). Solar flares deliver most of their energy periodically during only a few days out of an 11-year cycle; whereas, the cosmic ray flux is constant.

Although the lunar surface radiation flux is too high to spend much time in, it is definitely possible to alleviate the radiation danger with shielding. When colonists are removed from continuous exposure to surface radiation, long-term settlement becomes possible. As in the case of meteoroid protection, the simplest solution is to use locally available regolith for bulk shielding of habitats.

Silberberg et al. (1985) have suggested that a compacted layer of lunar regolith at least 2 meters thick should be placed over permanent habitats. With shielding of this thickness, the colonists' yearly exposure could be held to 5 rem per year if they spent no more than 20 percent of each Earth month on the surface. In order to provide an overall level of protection of no more than 5 rem per year even in the event of an extreme solar flare, such as occurred in February 1956, the depth of shielding would have to be doubled.

For the sake of completeness, it should be pointed out that some lunar regoliths contain a naturally radioactive component material known as KREEP. KREEP, probably a product of volcanism, contains radioactive potassium, uranium, and thorium. Material containing a high concentration of KREEP should not be used for shielding, and care should be taken to avoid concentrating it as shielding is prepared. The concentration of KREEP in most regolith material would add an amount of radioactivity no more than that in the granite used in buildings here on Earth. If the small contribution by KREEP to radiation dose is considered when exposures are calculated, it should not pose any significant health problem by itself.

It is a well-known fact that cosmic rays produce secondary particles, such as neutrons, upon collision with matter. These byproducts can add to the radiation exposure if the shielding is not "thick" enough to absorb the secondary neutrons as well. It turns out that the 15.2-cm-thick layer of compacted regolith proposed earlier for a meteoroid shield is not optimum. Obviously, if "thin" shielding is to be used, its utility must be examined in light of its disadvantages.

It seems likely that the initial lunar base will be constructed of modified space station modules, Space Shuttle external tanks, or similar pressure vessels. These pressure vessels will be transported to the lunar surface and placed in excavations. Once the modules are in place, they will be covered with the previously excavated regolith to provide shielding (see fig. 10). Land (1985) describes various approaches and consequences to providing support for the shielding above the pressurized enclosures. Logistically and structurally the use of bulk regolith is a convenient solution. Its use reduces the need to transport mass out of the Earth's gravity well and favors the transport of sophisticated value-added mass instead. Eventually, as the settlement begins to grow and develop industrial capability, locally available metals, glass, and bulk regolith can be fabricated into new facilities.

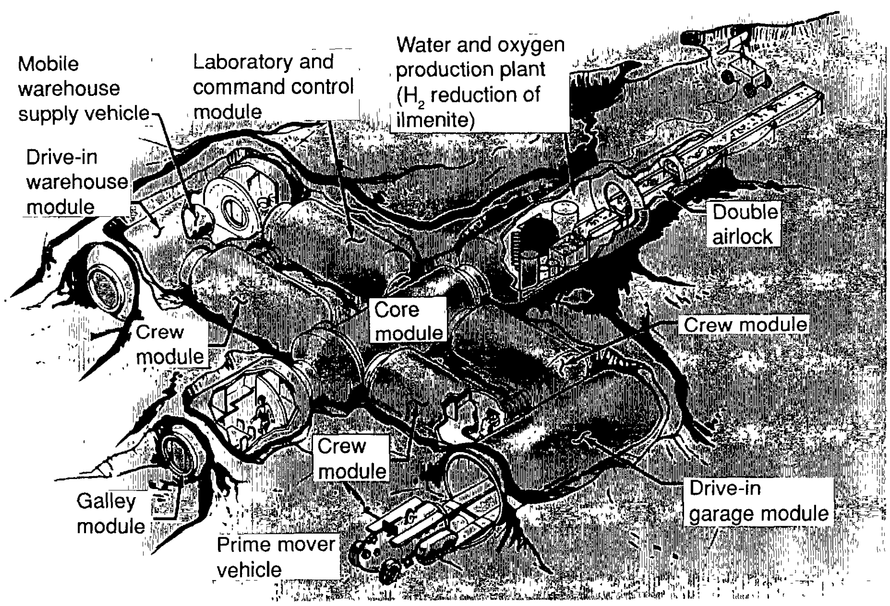


Figure 10

Lunar Base Modular Configuration

Initial base components could be made up of modified space station modules. The frontispiece shows how such modules might look in the panorama of a lunar base.

The advantage of using modified space station modules is that they will already have been designed, tested, and fabricated for use in space. The disadvantage is that a module designed for zero gravity and free space exposure might require major changes to fit the lunar environment with 1/6 g, ubiquitous dust, and the weight of piled-on regolith shielding.

Because of the nature of the lunar environment, much of the pioneers' time will be spent underground within their habitat modules. For safety and convenience, these modules will be linked together with tunnels (see fig. 11). While this underground environment will be different from Earth's standard, it need not be unpleasant or confining. By the time the base is under construction, manned operations on the space station will have provided a lot of useful experience in human factors engineering. Laboratories, factories, farms, and entertainment facilities will all be integrated into the underground installations on the Moon (see fig. 12). Some types of storage will also be underground, but a number of facilities will remain above ground.

Figure 11

Shielded Tunnels

The modules of a lunar base would be connected by tunnels, naturally shielded from surface hazards. The tunnels could be made airtight for use but would likely also be provided with airlocks for safety in case of depressurization.

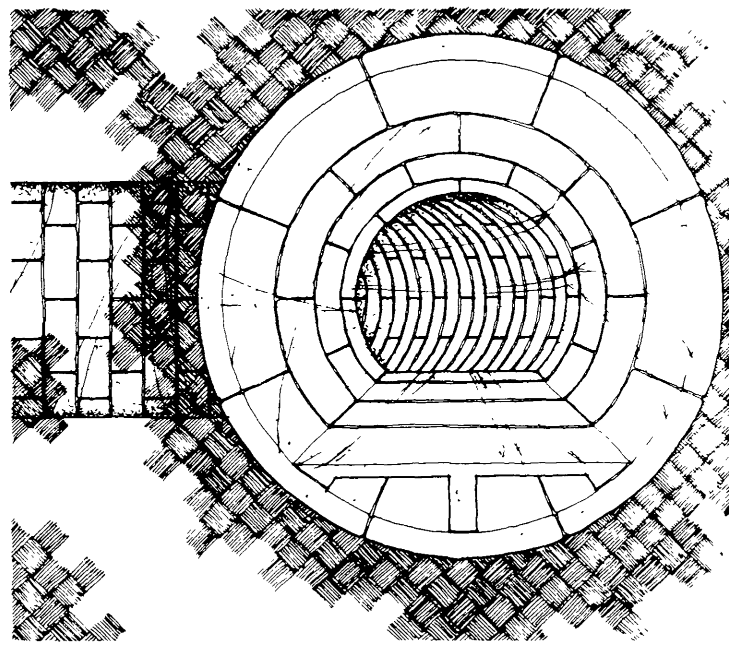
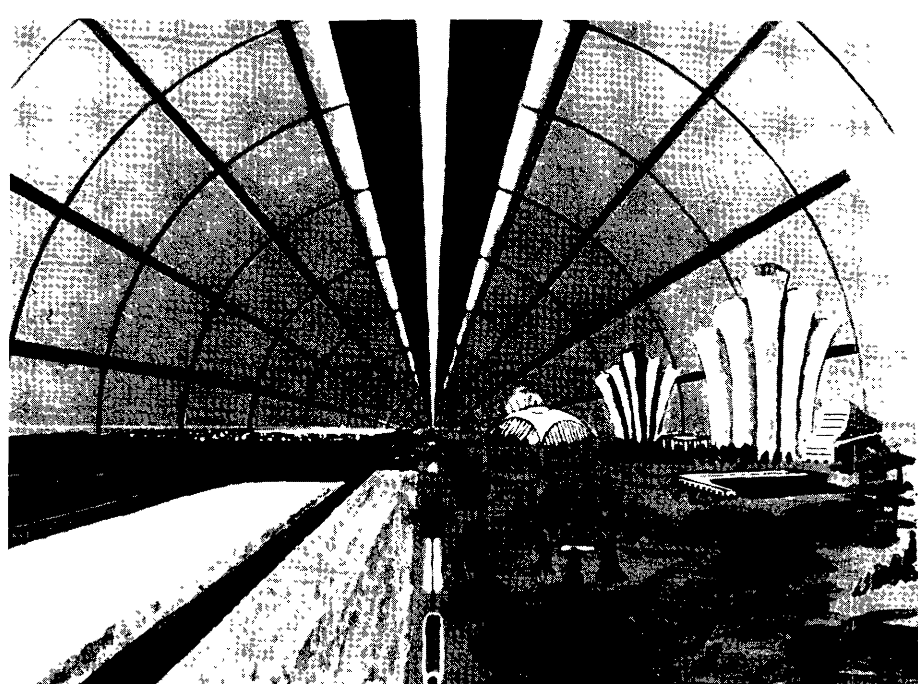


Figure 12

An Agricultural Zone in Krafft Ehricke's Selenopolis

Although the initial lunar outpost would no doubt be quite spartan, the expanding lunar base could be modified to make life under the lunar surface quite Earthlike and pleasant.



Transportation facilities such as hangars, landing pads, and refueling stations will be located on the lunar surface (see fig. 13). Power plants and communications superstructure will be surface installations as well. Some storage will be in surface warehouses (see fig. 14).

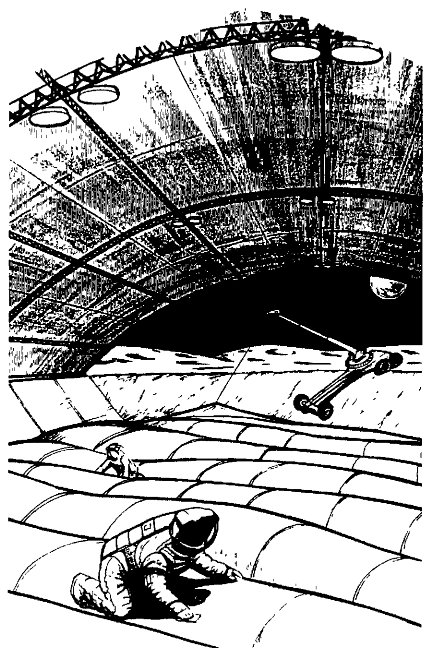


Figure 13

Lunar Hangars

Mobile surface equipment will need to be stored in protective hangars. Such hangars would provide shade against the Sun's heat during the 2-week-long lunar day and lighting for work during the equally long lunar night.

Artist: Pat Rawlings

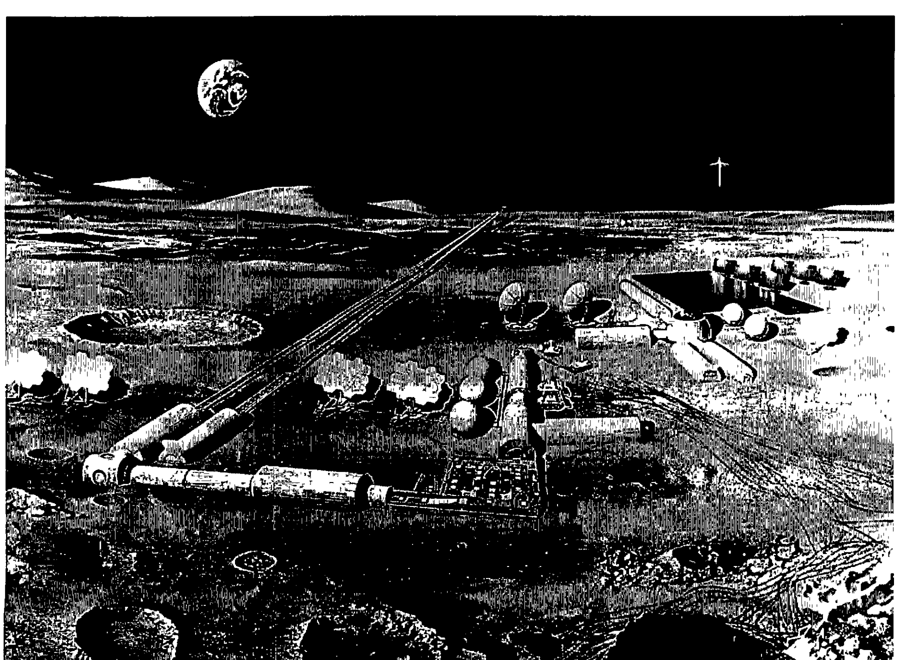


Figure 14

Lunar Surface Activities

Activities such as mining, transport, and processing will almost by necessity be conducted on the surface. While automation and teleoperation will be used extensively, some minimum amount of human tending will always be required. In this particular concept (from NASDA, the Japanese space agency), a processing plant produces oxygen and metals and an electromagnetic mass driver shoots these products into lunar orbit, where they can be used to support Earth-Moon space activities.

Strategies for Surface Operations

Although space suits appropriate to the lunar environment were successfully used during the Apollo missions, they are not the only means of conducting surface activities. Moon suits have several disadvantages, one problem being their limited duty cycle. Consumables, recycling systems, and operator fatigue are the most obvious limitations to how long a "moon walk" can last. The Apollo 14 astronauts walked everywhere and averaged about 4-1/2 hours per moon walk. By contrast, the Apollo 17 astronauts' surface activities, augmented by their use of the lunar roving vehicle (see fig. 15), averaged about 8 hours. Another constraint due to moon suit use is the time it takes to dress and undress (see fig. 16) and repair and refurbish the suits. Plenty of spare parts will probably be required. However, these difficulties are minor annoyances. The most serious problem with exclusive use of moon suits for surface activities is their insufficient meteoroid and radiation protection.

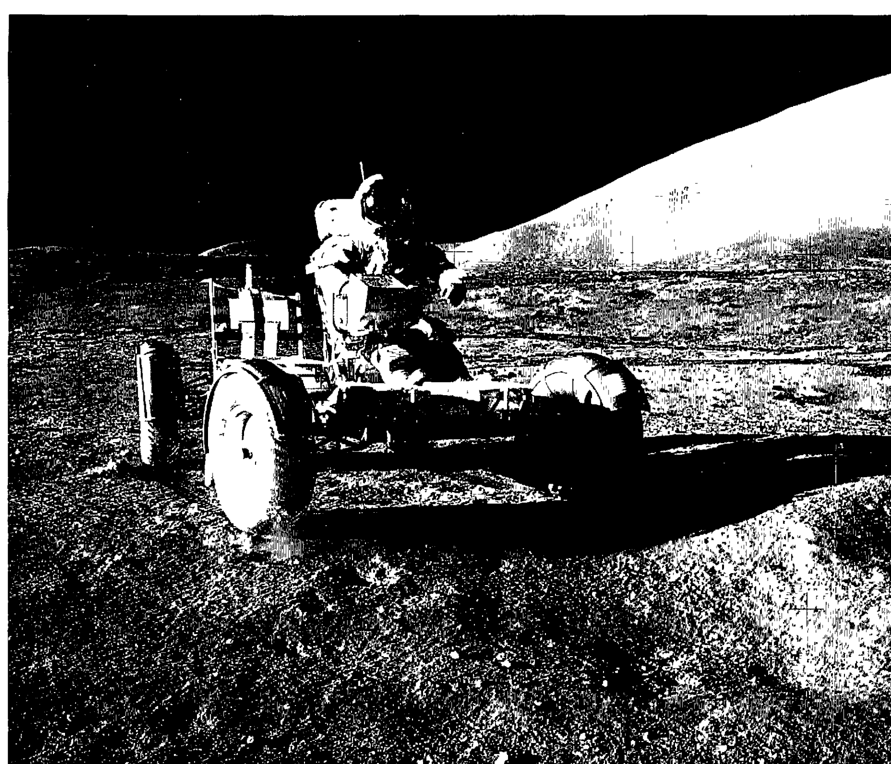


Figure 15

Lunar Rover

The use of the Apollo lunar Rover greatly increased the lunar explorers' effectiveness. Mobility will also be very desirable in lunar base operations and will be especially important for scientific exploration.

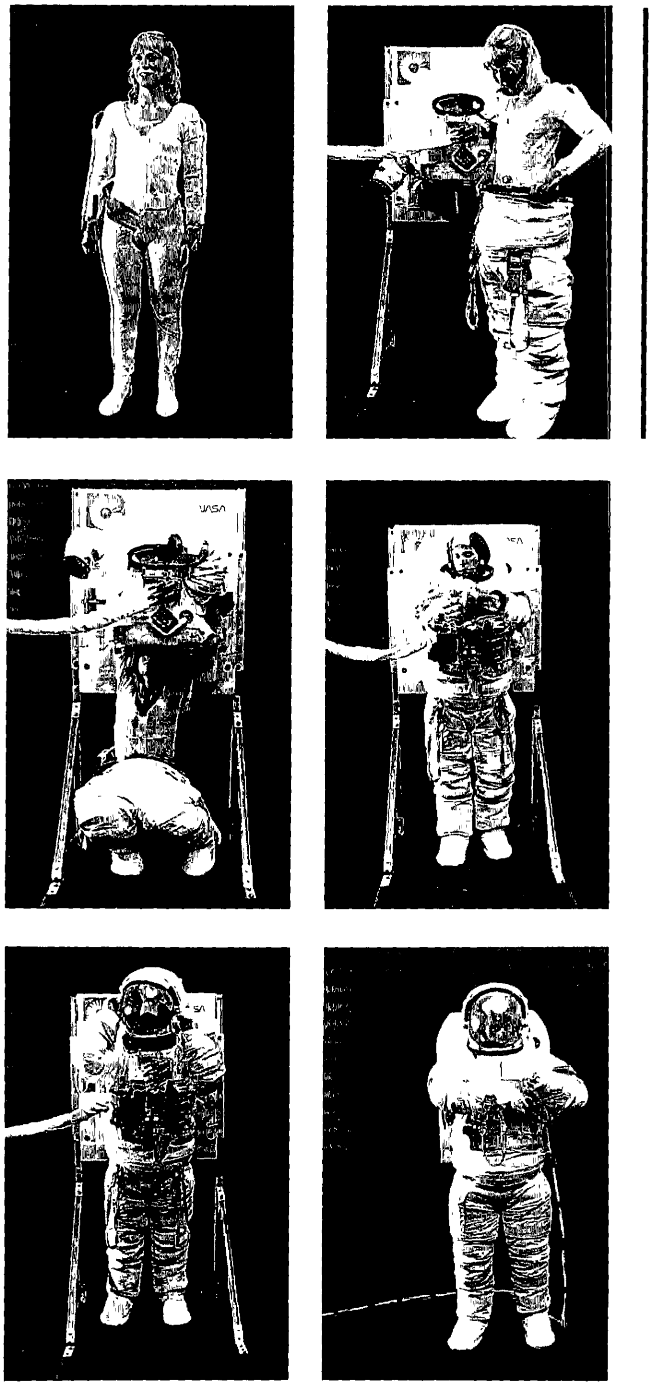
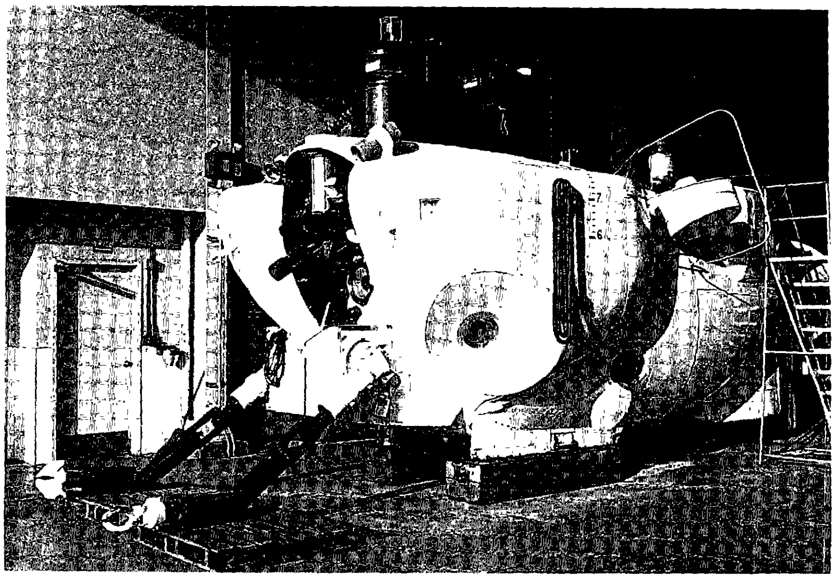


Figure 16

Suiting Up

Much time is consumed donning or doffing a space suit.

Therefore, the development of pressurized surface vehicles equipped with external tools and manipulators is desirable (see fig. 17). These vehicles would be analogous to the specialized submarines used for exploration, research, and repair in the Earth's oceans. Such devices provide their operators with a safe environment and permit access to a more hazardous one.



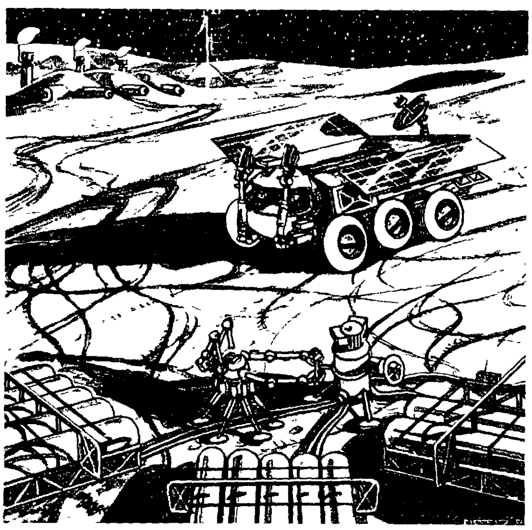


Figure 17

Vehicles for Operations in Hostile Environments

"Alvin" deep-diving research submarines protect their crews from the hostile ocean environment while permitting mobility and interaction within it. Cameras, floodlights, and portholes enhance the crew's visual access to their surroundings, and specialized manipulators and end effectors allow physical interaction. Inside the submarine, the crew is maintained in a shirt-sleeve environment. It seems highly likely that pressurized surface vehicles equipped with external tools will be developed to meet similar needs on the lunar surface.

If vehicles of this type were developed for use on the Moon, they would definitely have to provide meteoroid protection and the radiation protection necessary to keep the occupants' exposure well within the 50 rem/year limit [to the blood-forming organs (NCRP Report No. 98, July 31, 1989, p. 164)]. A thick layer of compacted regolith built into the hull may serve this purpose.

Another way to reduce radiation exposure problems might be to permit only older personnel (volunteers over 35 and people who have already had children) to spend much time on the surface and keep the younger personnel underground. This idea is based on the premise that delayed reactions to irradiation, like cancer, take long enough to develop that older people who are exposed may die of natural causes before the reaction occurs. However, this seems to be a solution of minimal merit. Every colonist will require an individual radiation dosimetry record and a "weather" forecast concerning the solar flare hazard whenever he or she leaves the habitat.

A truly satisfactory solution appears possible. Taking the manned vehicle concept one step further reveals another type of device, the teleoperated robot, which is well suited to the lunar environment. A teleoperated robot is a remotely controlled device which may be used to provide a human presence in a hazardous environment. Typically, the human operator directly controls the activities of the robot and receives feedback from it, so it is an electronic and mechanical extension of the person, essentially a surrogate body. Teleoperated robots have been used in the nuclear industry for years; they are finding applications in underwater work at great depths; and they have seen limited application in space.

Lunar teleoperators, like the ones shown in figure 18, could be operated in one of two modes: directly from the lunar habitat, as in figure 19, or indirectly from a space station or a facility on Earth. Each mode has its unique characteristics. Operation from Earth would be slower because of the several-second, round-trip radio signal delay. In this case, the teleoperated device may require built-in reflexes to protect itself, if the most recent command from Earth is in conflict with current local conditions. An example of this would be having the teleoperated device stop before walking or driving over the edge of a cliff which has just appeared on the operator's TV screen on Earth. In the early 1970s, the Russians successfully demonstrated the usefulness of their Lunokhod teleoperated roving vehicles on the Moon (see fig. 20).

It has been commonly thought that the main problem faced by Earth-based operators who "commute" to work on the Moon by radio would be severe fatigue and frustration due to the timelag. To evaluate this possibility, I conducted a series of lunar-time-delay manipulation and mobility experiments using a mobile robot equipped with a 4-degree-of-freedom manipulator arm (see fig. 21). My results (1989) indicate that the 3-sec delay inherent in round-trip communication between the Earth and the Moon is not a significant barrier to teleoperated manipulation and mobility. With proper system design, this mode of operation will, at worst, require patient people and predictive positioning aids.

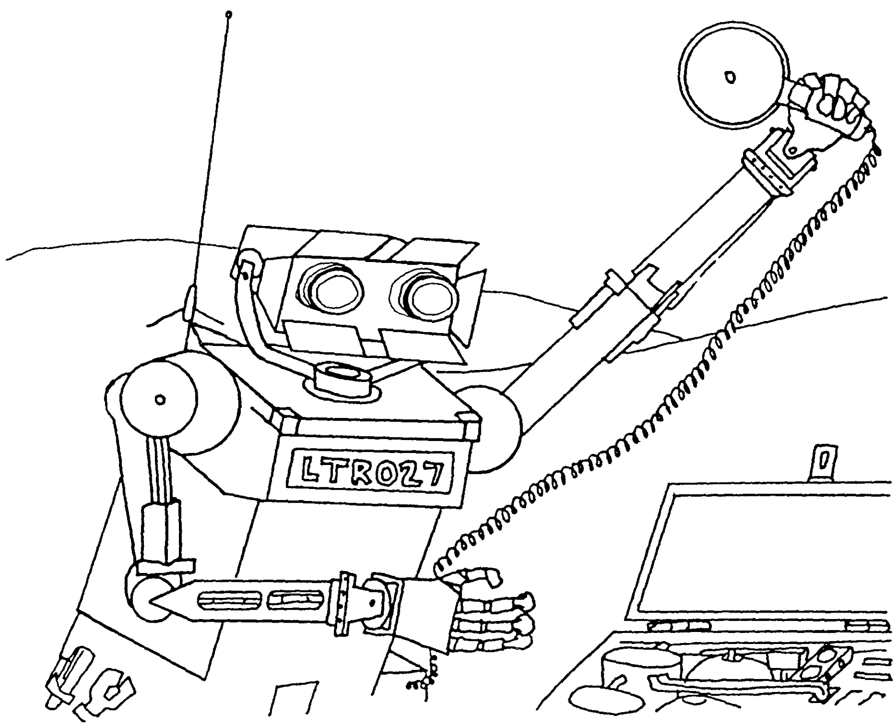
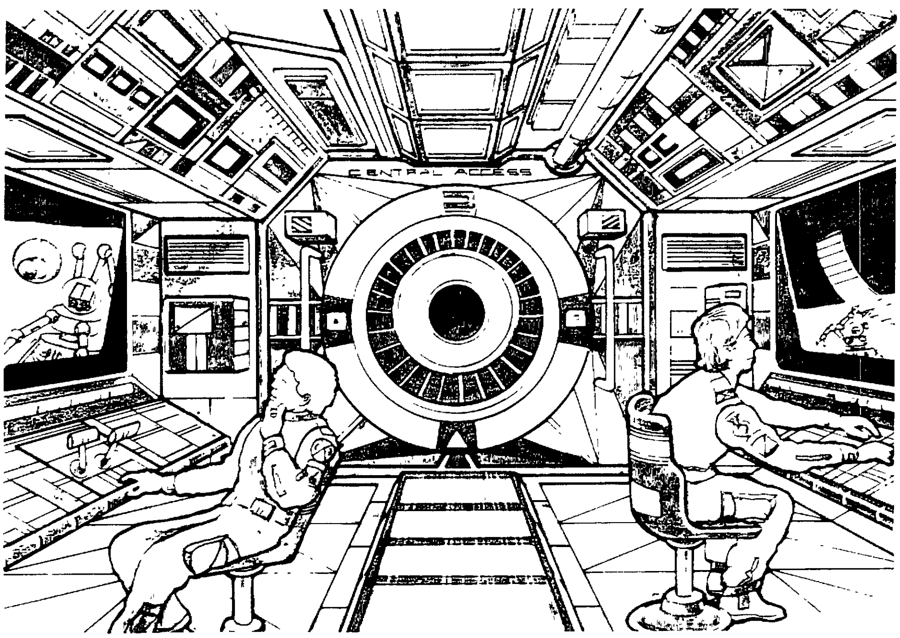


Figure 18

Teleoperated Robot

Teleoperated robots will be designed to provide a human presence on the lunar surface. This robot's arms have the same freedom of movement as human arms: three degrees at the shoulder, one at the elbow, and three at the wrist. Its hands are modeled on human hands but require only three fingers and a thumb. The robot's head can turn up and down, right and left. It has two TV cameras for stereo vision (with glare shades, which are movable on hinges).



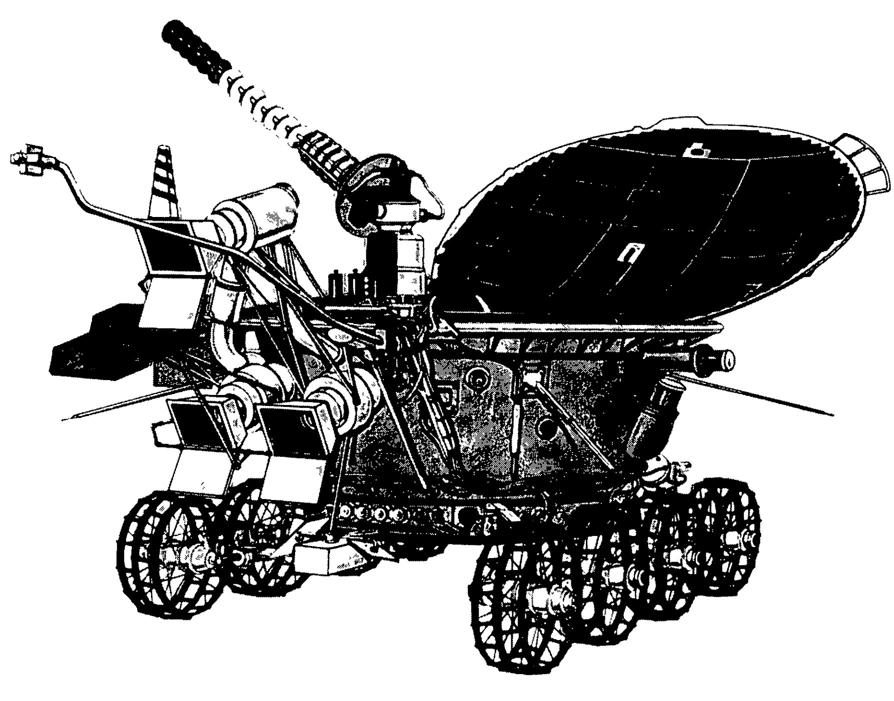


Figure 19

Teleoperations Control Center Underground at the Lunar Base

Surface activities could easily be directed from comfortable underground facilities. Such control centers would provide safe environments for lunar workers who would otherwise be required to do routine jobs in a hazardous environment. Each operator could supervise the activities of many semi-autonomous robots or directly control one telerobot to apply more specialized skills to the task at hand. Although the two human operators shown are controlling and monitoring telerobotic equipment at two different locations, they could just as easily be coordinating their teleoperations. Such a team effort could even be assisted by additional controllers located at other sites on the Moon or elsewhere, as long as there were enough telerobots at the work site and sufficient communications channels. Keep in mind that the controllers would always have the option to shut down their telerobots temporarily so that they could take a personal break or attend immediately to another matter within the base without losing travel or space suit removal time or wasting limited excursion supplies like oxygen.

Figure 20

Lunokhod

Automated vehicles roving over another planetary body were first used in the early 1970s by the Soviets on their Lunokhod missions. These lunokhods were capable of traveling tens of kilometers at speeds up to 2 km/hr. They were run from a Soviet control center by a crew of five—commander, driver, navigator, operator, and onboard-systems engineer. The crew used slow-scan television images and systems readouts to drive and operate the vehicles.

Figure 21

SSI Teleoperations Simulation Chamber

The Space Studies Institute in Princeton, NJ, has been involved in a continuing experiment to evaluate the usefulness of time-delayed teleoperation under lunar conditions. Here the designers, Rob Lewis and David Brody, demonstrate a telerobotics facility to Jean-Loup Chrétien, who has been a guest cosmonaut. The facility consists of an operator control console and a simulated lunar environment chamber (with its side cover removed to reveal the interior). On the far right, a mobile robot equipped with a 4-degree-of-freedom manipulator can be seen interacting with a workstation while under the time-delayed control of the operator. Although the operator receives video from inside the chamber, direct visual access into it is not possible during experiment runs. The chamber has been optimized to visually replicate lunar conditions when viewed with video cameras.

Photo: Barbara Faughnan

Local use of teleoperated devices would not be hampered by time delays, but it would require additional relay stations, such as comsats or mountaintop repeaters, to overcome the obstacles to line-of-sight radio propagation on the lunar surface. It seems likely that teleoperated robots will be controlled from Earth, from the Moon, and from points in between.

Teleoperated robots will not replace people; rather they will enhance a person's capabilities. As mentioned earlier, the teleoperated robot may be controlled in a master-slave mode, given sufficient feedback to allow the human operator to sense and react to the robot's environment as if the person were there. Another control approach uses "supervised autonomy." Supervised autonomy involves a working partnership between a human, who sets goals and supervises their implementation, and a more fully automated robot, which is responsible for carrying out specific tasks. Much less feedback would be necessary using this strategy.

Sending a number of teleoperated machines to the Moon to prepare the way for later colonists may be warranted. This would have the twin advantages of maximizing safety and limiting the cost of the initial missions, as local materials could be used to prepare a base and supplies before the people moved in. Once the settlement was occupied, teleoperators controlled from Earth would act as "force multipliers." They could be run by several shifts of operators on Earth each day (including weekends). Thus, each machine could do the work of three or more lunar colonists, without the costs of bringing those colonists to the Moon and providing life support for them. In addition, teleoperated devices could potentially permit experts from Earth to provide timely services otherwise unavailable locally.

Teleoperated machines used in conjunction with a manned base could be regularly repaired and rebuilt by the lunar staff as required by changing needs. We should remember that teleoperated machines are far less sensitive to radiation than people and can be optimized for their environment and tasks. If a teleoperator is hit by a meteoroid, it may possibly be repaired or salvaged. If not, it certainly is more expendable than a person. Thus, the development of teleoperators for lunar surface use is definitely worth further investigation.

The Moon is an ideal "large" space station and offers many advantages over other near-Earth locations, such as natural gravity and useful resources. Extensive human activities on the Moon will be constrained initially by the lunar environment because it is so different from the Earth's. Means to ease these constraints are possible and should be pursued. There is much to be gained from a permanent human presence on the Moon.

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Summer Study Postscript: A 1986 Perspective

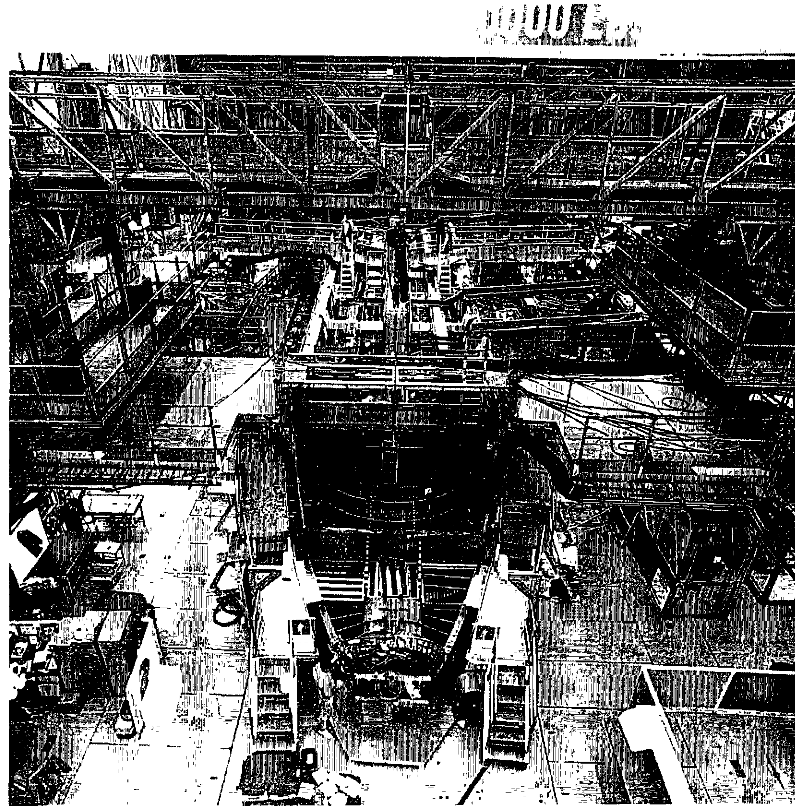
Philip R. Harris et al.

Now that the National Commission on Space has set out bold goals and strategies for the American space program in the next 50 years, how can we turn such visions into realities? Since the *Challenger* tragedy and other space failures have brought about a crisis of confidence in NASA, what innovations are necessary to rebuild public consensus and support? What initiatives can the private sector take to promote the peaceful use of space by its exploration and industrialization? The faculty fellows from the 1984 summer study propose three possibilities for action by NASA and supporters of the space program.

A National Lottery for Space Enterprises

Public lotteries to support exploration and civilizing ventures on new frontiers are part of the Nation's tradition. They were used by the English to support the Jamestown colonization and to open the western frontier. They have become popular again in this century as a means of raising money for state governments. Such a lottery could alleviate the national tax burden imposed by the plans of the National Commission on Space, which they estimate to cost $700 billion.

As a step to providing the vigorous leadership on the space frontier called for by these commissioners, either the Congress or a private consortium or a combination of public and private leaders might launch this national lottery. The first target would be to obtain funding for a fourth orbiter, to be devoted exclusively to scientific, commercial, and international use. Named "Challenger II," it would be a public memorial and expression of appreciation to the seven crewmembers who lost their lives in the first shuttle of that name. Once the Shuttle fleet was back to full capacity, the next objective might be funding for more advanced aerospace planes. Just as the Conestoga wagons and the railroad opened up new resources in the West, so will these initial vehicles on the space "highway."



A Fourth Orbiter

The Endeavour, *expected to bring NASA's Shuttle fleet to four again, is seen under construction at Rockwell's manufacturing facility in California.*

Continued fundraising of this type would be designated to help underwrite the space infrastructure that will enable us to tap space resources (e.g., the construction of the space station and lunar or martian bases of operation).

How? As the National Commission on Space gathered its input, hundreds of individuals in 15 public forums contributed their ideas. Such people, along with the space advocacy groups, could provide the momentum for this National Lottery for Space Enterprises. At the present time, there are 50 groups advocating the development of space. They have a collective membership of 300 000 and an aggregate annual budget of $30.5 million. All these, together with other space business leaders and entrepreneurs, could provide the thrust to translate the lottery proposal into dollars for space enterprise. Readers of such magazines as *Aviation Week & Space Technology* and *Commercial Space* could be enlisted in such a campaign. Gradually, beginning with Canada, the lottery could be extended internationally. We suggest Lee Iacocca and his leadership of the campaign to restore the Statue of Liberty as an example of the type of citizen and strategy needed in this next national endeavor. "We the people of the United States of America" can implement the goals set forth by the National Commission on Space.

A White House Conference on Space Enterprise

Another step to encourage civilian leadership in the American space program would be a White House conference. Space planners and advocates should urge their congressional representatives to introduce a bill supporting such a convocation and calling upon the Administration to issue invitations and set an agenda. The primary purpose of the conference would be to examine ways to implement the recommendations of the National Commission on Space, thereby opening up the space frontier and improving the quality of life here on Earth. The secondary purpose would be to develop a national consensus on the peaceful and commercial exploration and utilization of space resources.

A White House Conference

The faculty fellows in this NASA summer study group urge that a White House conference be called to find ways and means to implement the recommendations of the National Commission on Space, thereby opening up the space frontier and improving the quality of life here on Earth.

Photo: Joyce C. Naltchayan

A call by the President to carry out the space commission's goals* would boost American morale, turn our energies outward, and ensure the country's space leadership into the 21st century. To recharge the national enthusiasm for space, distinguished Americans and other guests would be invited to this conference to propose immediate and pragmatic means for reaching the commission's targets. The planners might invite corporations in the space business to join the Government in sponsoring the event. The participants would include not only space professionals but also people of competence and distinction in positions to influence the citizenry in their support of space activities. We suggest Walter Cronkite as the type of person capable of communicating the message from such a White House conference and enlisting public support. The aim would be to obtain massive media attention not only to the conference but also to its results.

The proposed White House conference might be structured on a theme set forth by the National Commission: "Stimulating space enterprises for the direct benefit of the people on Earth." The sessions might be organized around the four parts of the commission's report—civilian space goals for 21st century America, low-cost access to the solar system, opening the space frontier in the next 20 years, American leadership on the space frontier in the next 50 years.

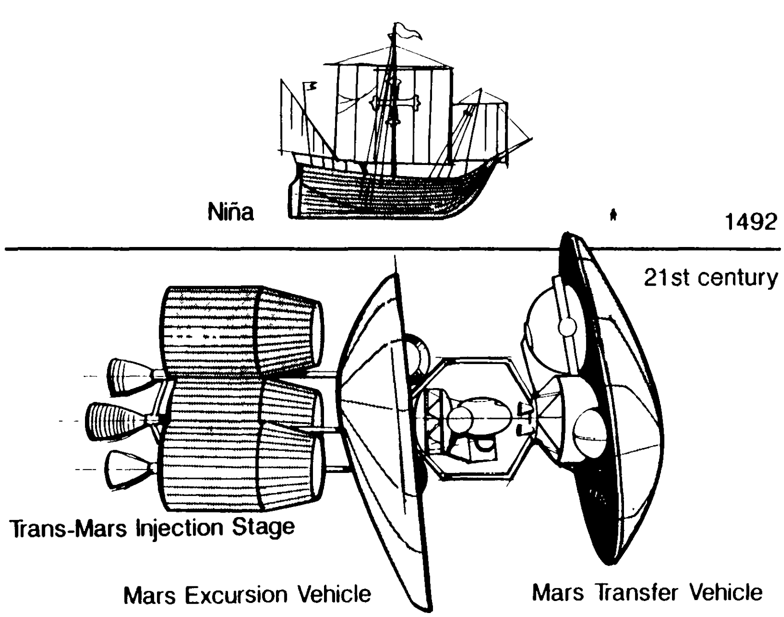
Reorganization of the National Aeronautics and Space Administration

If the goals and recommendations set forth by the National Commission on Space are to be achieved, then NASA needs to be renewed and reorganized. The internal renewal of its organizational culture and management is already under way as a result of the findings of the Presidential Commission on the Space Shuttle Challenger Accident. But reorganization in the charter and structure of the agency might enable it to become more free of the Federal bureaucracy, annual budget battles, and political pressures that undermine its ability to make strides in space.

*Such a call was issued by President George Bush in his July 20, 1989, speech on the steps of the Smithsonian Air and Space Museum. Specifically, he proposed commitment to three of the Commission's twelve technological milestones in space: Space Station *Freedom*, a permanent lunar outpost, and human exploration of Mars.

In 1984, the faculty fellows of the NASA summer study recommended that legislation be passed to strengthen NASA by making it more autonomous. (Models exist in the U.S. Postal Service, the Tennessee Valley Authority, and the New York Port Authority.) By creating a National Aeronautics and Space Authority as a semiautonomous corporation, our Nation's leaders would allow the NASA budget to be set for long-term project development. The funding for research and development could be separated from that for operations. Such legislative changes might enable NASA to enter into joint ventures with the private sector in the United States and abroad, as well as with other national space entities, so as to supplement its income beyond Government appropriations. Then, creative financing of space ventures might be discovered through the issuance of bonds or the sale of stock in limited R&D partnerships or in space trading companies. (Shades of the Dutch East India Company!) Because of the scope and complexity of space development, NASA needs to be empowered to give leadership in promoting the cooperative efforts of Government, universities, and industry in the furtherance of human enterprise in space.

Ships of Exploration



Ships of Exploration

"From the voyages of Columbus to the Oregon Trail to the journey to the Moon itself, history proves that we have never lost by pressing the limits of our frontiers," said President George Bush on the 20th anniversary of the Apollo 11 landing on the Moon. The President urged that we press the limits of our frontiers on to another planet and make a journey to Mars

Our Niña (and Pinta and Santa Maria) might look like this A trans-Mars injection stage, essentially large propellant tanks with rocket motors attached (Columbus' ships didn't have to carry their propellant), to propel the ship from Earth to Mars. A Mars excursion vehicle, with its aerobrake to slow the descent into Mars orbit (we, too, will make use of the "wind") and its martian lander And a Mars transfer vehicle, also equipped with an aerobrake and much smaller rocket motors, to enter Mars orbit and bring the crew home.

Addendum: Participants

The managers of the 1984 summer study were

David S. McKay, Summer Study Co-Director and Workshop Manager
Lyndon B. Johnson Space Center

Stewart Nozette, Summer Study Co-Director
California Space Institute

James Arnold, Director
of the California Space Institute

Stanley R. Sadin, Summer Study Sponsor
for the Office of Aeronautics and Space Technology
NASA Headquarters

Those who participated in the 10-week summer study as faculty fellows were the following:

James D. Burke	Jet Propulsion Laboratory
James L. Carter	University of Texas, Dallas
David R. Criswell	California Space Institute
Carolyn Dry	Virginia Polytechnic Institute
Rocco Fazzolare	University of Arizona
Tom W. Fogwell	Texas A & M University
Michael J. Gaffey	Rensselaer Polytechnic Institute
Nathan C. Goldman	University of Texas, Austin
Philip R. Harris	California Space Institute
Karl R. Johansson	North Texas State University
Elbert A. King	University of Houston, University Park
Jesa Kreiner	California State University, Fullerton
John S. Lewis	University of Arizona
Robert H. Lewis	Washington University, St. Louis
William Lewis	Clemson University
James Grier Miller	University of California, Los Angeles
Sankar Sastri	New York City Technical College
Michele Small	California Space Institute

Participants in the 1-week workshops included the following:

Constance F. Acton	Bechtel Power Corp.
William N. Agosto	Lunar Industries, Inc.
A. Edward Bence	Exxon Mineral Company
Edward Bock	General Dynamics
David F. Bowersox	Los Alamos National Laboratory
Henry W. Brandhorst, Jr.	NASA Lewis Research Center
David Buden	NASA Headquarters
Edmund J. Conway	NASA Langley Research Center
Gene Corley	Portland Cement Association
Hubert Davis	Eagle Engineering
Michael B. Duke	NASA Johnson Space Center
Charles H. Eldred	NASA Langley Research Center
Greg Fawkes	Pegasus Software
Ben R. Finney	University of Hawaii
Philip W. Garrison	Jet Propulsion Laboratory
Richard E. Gertsch	Colorado School of Mines
Mark Giampapa	University of Arizona
Charles E. Glass	University of Arizona
Charles L. Gould	Rockwell International
Joel S. Greenberg	Princeton Synergetics, Inc.
Larry A. Haskin	Washington University, St. Louis
Abe Hertzberg	University of Washington
Walter J. Hickel	Yukon Pacific
Christian W. Knudsen	Carbotek, Inc.
Eugene Konecci	University of Texas, Austin
George Kozmetsky	University of Texas, Austin
John Landis	Stone & Webster Engineering Corp.
T. D. Lin	Construction Technology Laboratories
John M. Logsdon	George Washington University
Ronald Maehl	RCA Astro-Electronics
Thomas T. Meek	Los Alamos National Laboratory
Wendell W. Mendell	NASA Johnson Space Center
George Mueller	Consultant
Kathleen J. Murphy	Consultant
Barney B. Roberts	NASA Johnson Space Center
Sanders D. Rosenberg	Aerojet TechSystems Company
Robert Salkeld	Consultant
Donald R. Saxton	NASA Marshall Space Flight Center
James M. Shoji	Rockwell International
Michael C. Simon	General Dynamics
William R. Snow	Electromagnetic Launch Research, Inc.
Robert L. Staehle	Jet Propulsion Laboratory
Frank W. Stephenson, Jr.	NASA Headquarters
Wolfgang Steurer	Jet Propulsion Laboratory
Richard Tangum	University of Texas, San Antonio
Mead Treadwell	Yukon Pacific
Terry Triffet	University of Arizona
J. Peter Vajk	Consultant
Jesco von Puttkamer	NASA Headquarters
Scott Webster	Orbital Systems Company
Gordon R. Woodcock	Boeing Aerospace Company

The following people participated in the summer study as guest speakers and consultants:

Edwin E. "Buzz" Aldrin	Research & Engineering Consultants
Rudi Beichel	Aerojet TechSystems Company
David G. Brin	California Space Institute
Joseph A. Carroll	California Space Institute
Manuel I. Cruz	Jet Propulsion Laboratory
Andrew H. Cutler	California Space Institute
Christopher England	Engineering Research Group
Edward A. Gabris	NASA Headquarters
Peter Hammerling	LaJolla Institute
Eleanor F. Helin	Jet Propulsion Laboratory
Nicholas Johnson	Teledyne Brown Engineering
Joseph P. Kerwin	NASA Johnson Space Center
Joseph P. Loftus	NASA Johnson Space Center
Budd Love	Consultant
John J. Martin	NASA Headquarters
John Meson	Defense Advanced Research Projects Agency
Tom Meyer	Boulder Center for Science and Policy
John C. Niehoff	Science Applications International
Tadahiko Okumura	Shimizu Construction Company
Thomas O. Paine	Consultant
William L. Quaide	NASA Headquarters
Namika Raby	University of California, San Diego
Donald G. Rea	Jet Propulsion Laboratory
Gene Roddenberry	Writer
Harrison H. "Jack" Schmitt	Consultant
Richard Schubert	NASA Headquarters
Elie Shneour	Biosystems Associates, Ltd.
Martin Spence	Shimizu Construction Company
James B. Stephens	Jet Propulsion Laboratory
Pat Sumi	San Diego Unified School District
Robert Waldron	Rockwell International
Simon P. Worden	Department of Defense
William Wright	Defense Advanced Research Projects Agency

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National Aeronautics and
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Lyndon B. Johnson Space Center
Houston, Texas 77058